Association of Engineering Geologists
1992-Annual Meeting
Hosted by the AEG
Southern California Section

Groundwater Monitoring and Remediation Techniques Short Course

Monday - October 5, 1992 - 8 Hours Duration

Sheraton Long Beach Hotel, 333 E. Ocean Boulevard, Long Beach, California

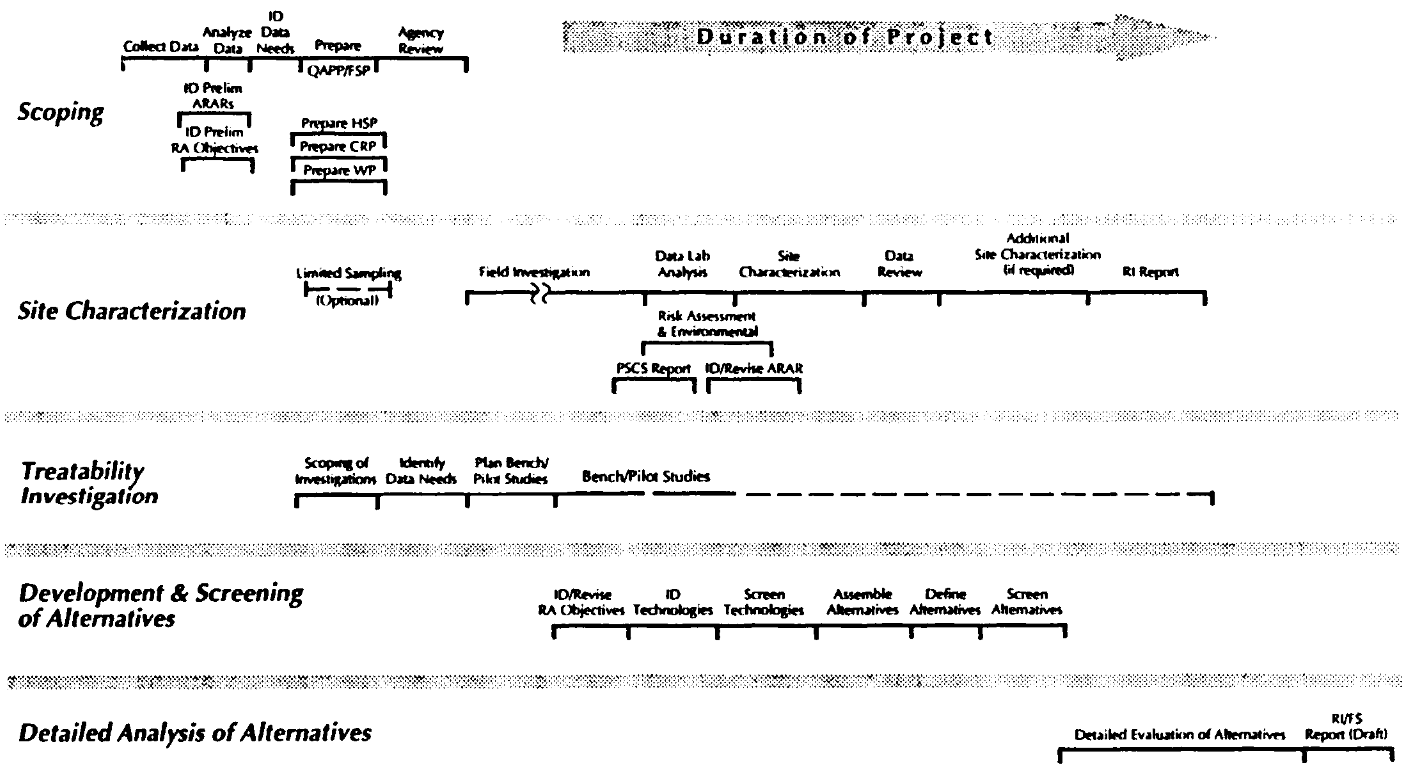
Instructors

Kelly E. Rowe, C.E.G.
Victor E. Harris, C.E.G.
Donn Marrin, Ph.D.
Robert Evangelista

Acronyms Related to Superfund

ARAR -	Applicable or relevant and appropriate requirement
CERCLA -	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CRP -	Community Relations Plan
DQO -	Data Quality Objectives
FSP -	Field Sampling Plan
HSP -	Health & Safety Plan
IRA -	Interim Remedial Action
PA -	Preliminary Assessment
PSCS -	Preliminary Site Characterization Study
QAPP -	Quality Assurance Project Plan
RA -	Remedial Action
RAP -	Remedial Action Plan
RI/FS -	Remedial Investigation/Feasibility Study
ROD -	Record of Decision
SARA -	Superfund Amendments and Reauthorization Act of 1986
SI -	Site Investigation
WP -	Work Plan

Generic Phased Remedial Investigation/Feasibility Study Timeline



Acronyms

ARAR - Applicable or relevant and appropriate requirement
CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CRP - Community Relations Plan
DQO - Data Quality Objectives
FSP - Field Sampling Plan
HSP - Health & Safety Plan
PSCS - Preliminary Site Characterization Study
QAPP - Quality Assurance Project Plan
RA - Remedial Action
RI/FS - Remedial investigation/feasibility Study
SARA - Superfund Amendments and Reauthorization act of 1986
WP - Work Plan

RI/FS Timeline

Groundwater Monitoring and Remediation Techniques Short Course

Definitions of Acronyms Related to Laboratory Analyses

Detection and Quantitation Limits

Contract Required Detection Limit (CRDL)- The minimum level of detection acceptable under the CLP Statement of Work for Inorganics Analysis.

Contract Required Quantitation Limits (CRQL)- Minimum level of quantitation acceptable under the CLP Statement of Work for Organics Analysis.

Instrument Detection Limit (IDL)- Smallest signal above background noise that an instrument can detect reliably.

Limit of Detection (LOD)- The lowest concentration that can be determined to be statistically different from a blank.

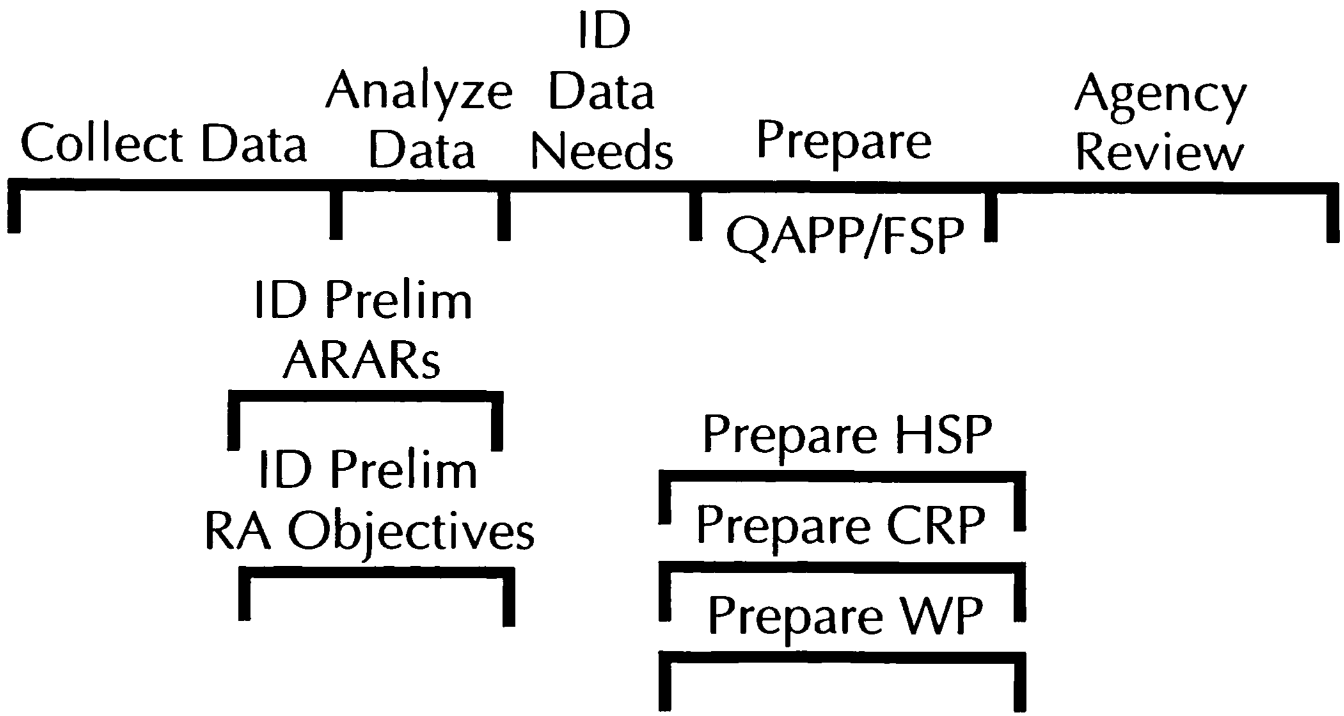
Limit of Quantitation (LOQ)- The concentration above which quantitative results can be obtained with a specified degree of confidence.

Method Detection Limit (MDL)- The minimum concentration of an analyte that can be determined with 99 percent confidence that the true valued is greater than zero.

Method Quantification Limit (MQL)- The minimum concentration of a substance that can be measured and reported.

Practical Quantitation Limit (PQL)- The lowest level that can be reliable achieved within specified limits of precision and accuracy during routine laboratory operation conditions.

RI/FS Initial Tasks
Scoping



RI/FS Treatability Investigation & Alternative Remedial Action Analysis Tasks

Treatability Investigation

Scoping of Investigations | Identify Data Needs | Plan Bench/ Pilot Studies | Bench/Pilot Studies

Development & Screening of Alternatives

ID/Revise RA Objectives | ID Technologies | Screen Technologies | Assemble Alternatives | Define Alternatives | Screen Alternatives

RI/FS Site Characterization Tasks

**Limited Sampling (Optional)
before these tasks**

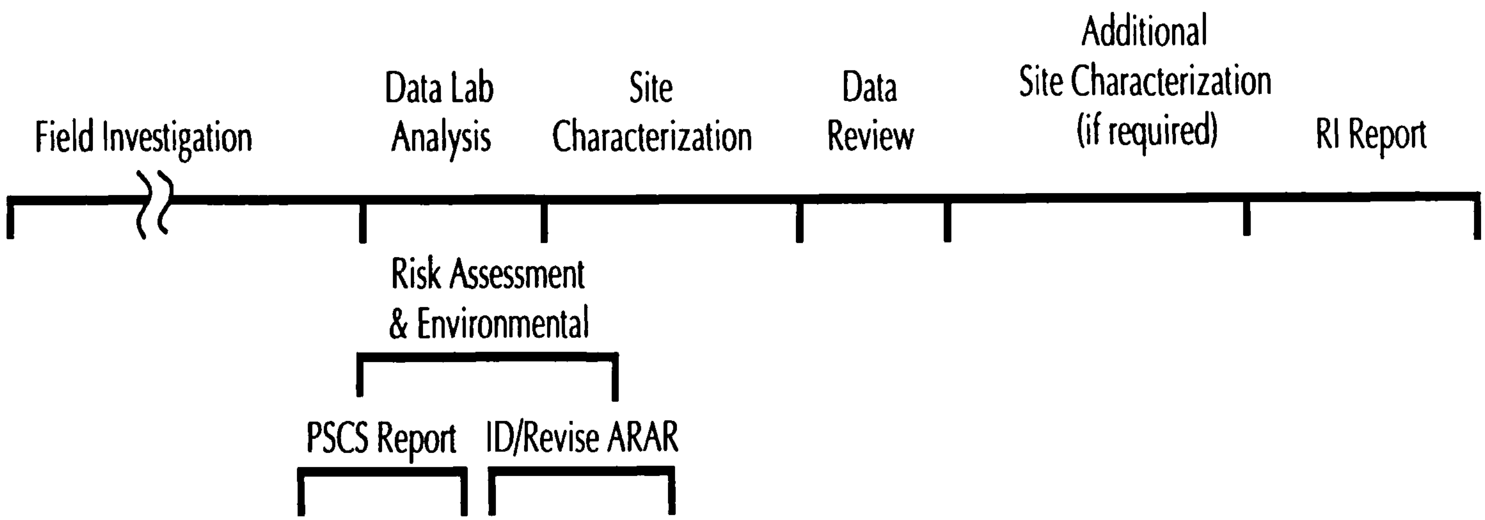


Diagram of Cable Tool Drilling Method

(from Buckeye Drill Co./Bucyrus-Erie Co., 1982)

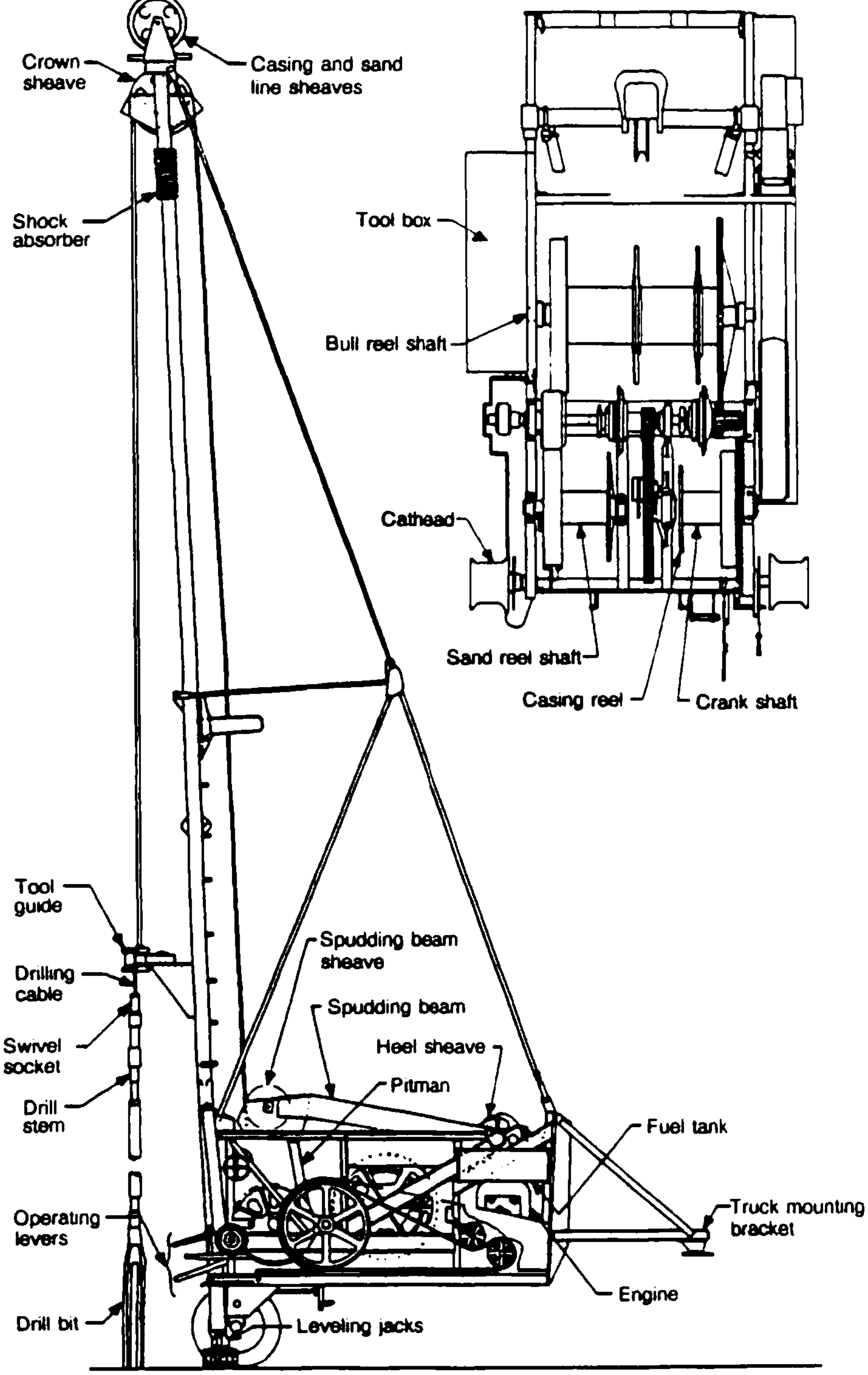


Diagram of Components of Hollow-Stem Auger Drilling Method

(from Central Mine Equipment Co., 1987)

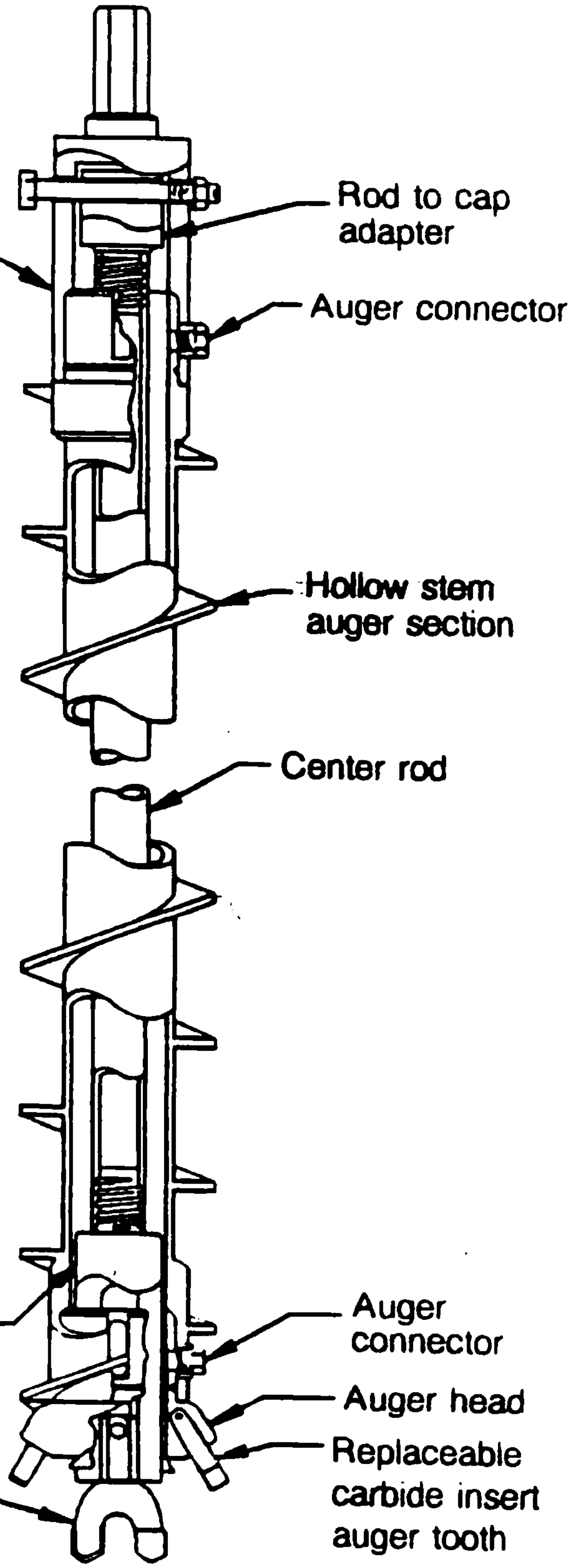


Diagram of Direct Rotary Drilling Method

(from National Water Well Assoc. of Australia, 1984)

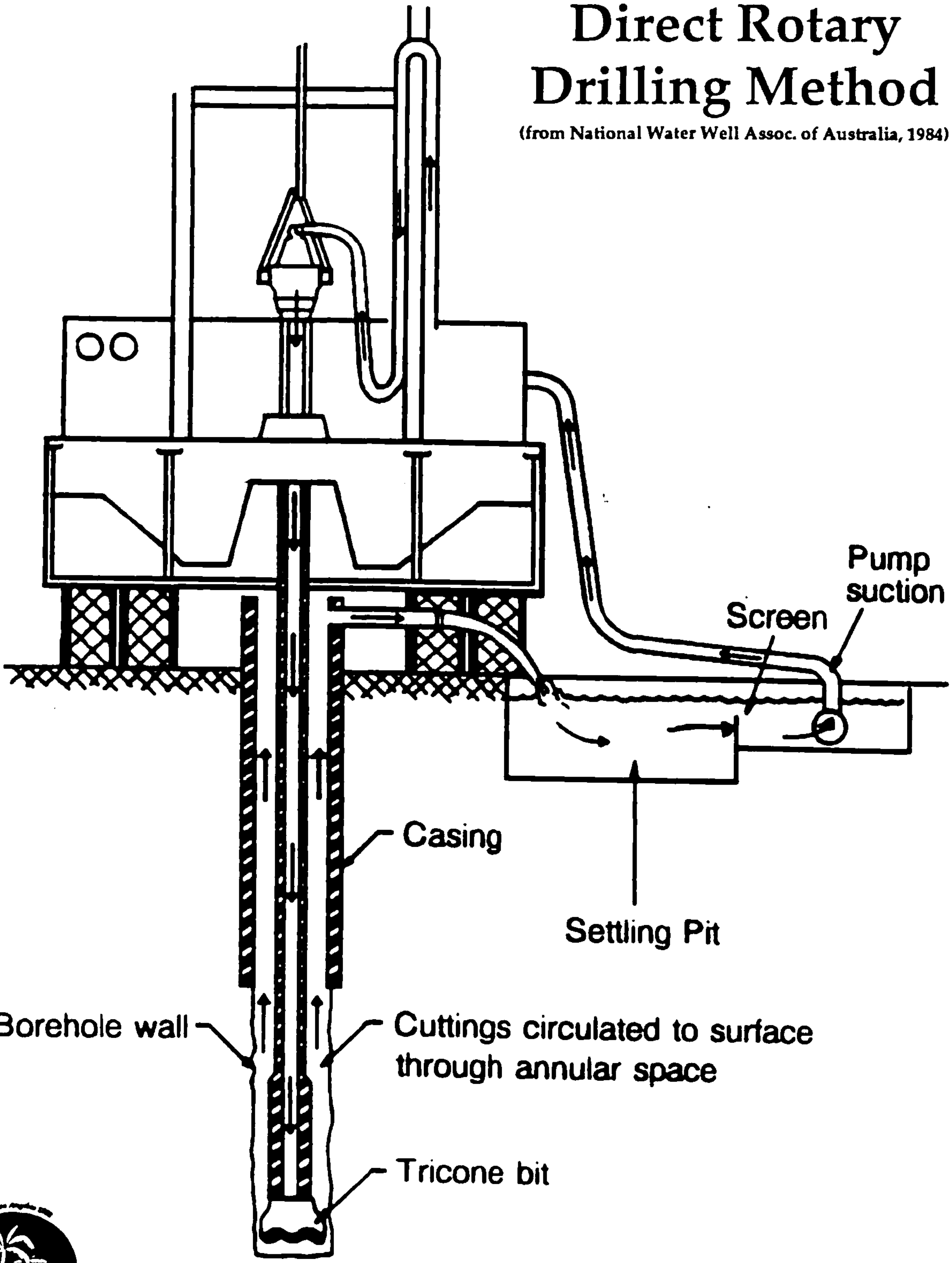


Diagram of Air Rotary/ Casing Hammer Drilling Method

(from Aardvark Corp., 1977)

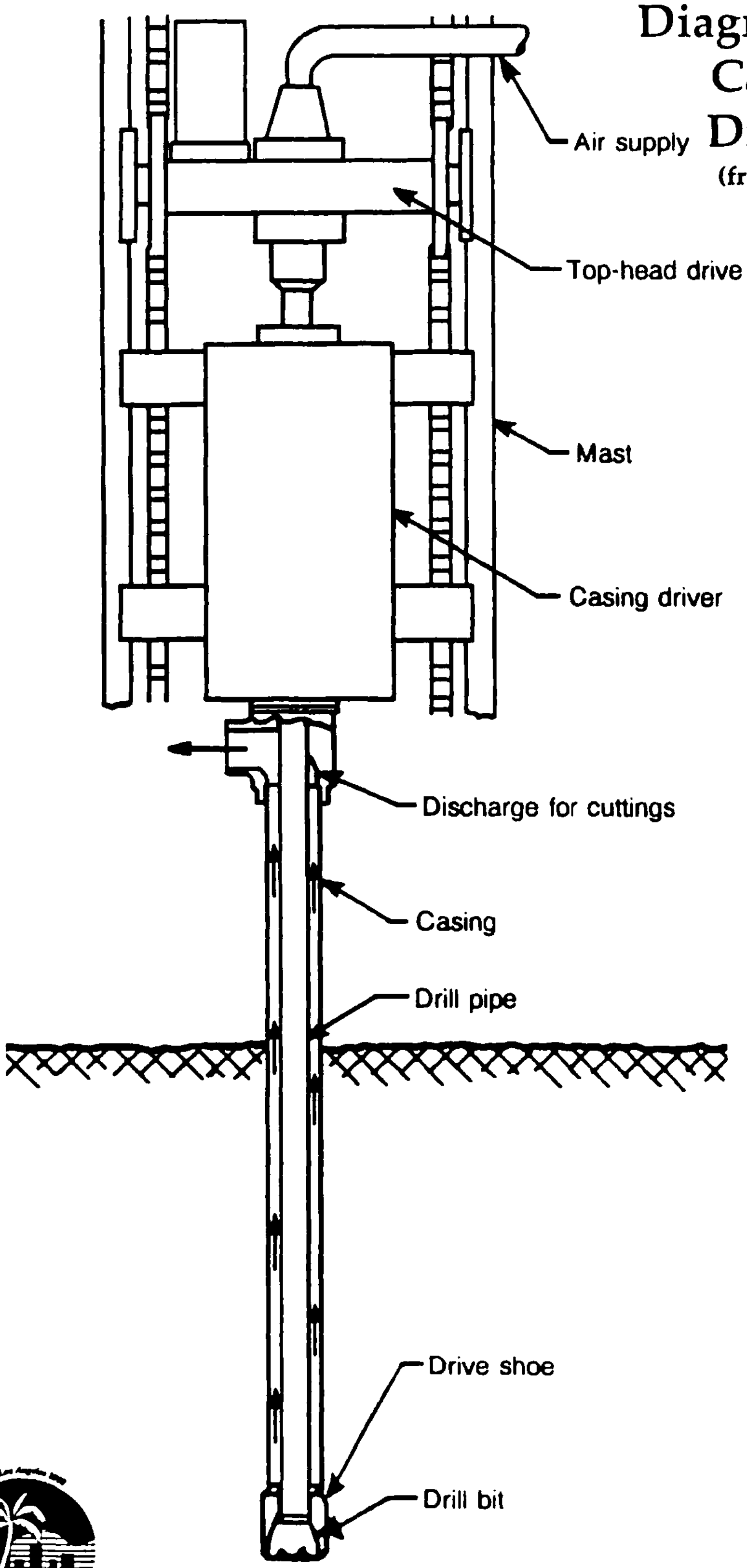


Diagram of Dual-Wall Reverse-Circulation Rotary Drilling Method

(from Driscoll, 1986)

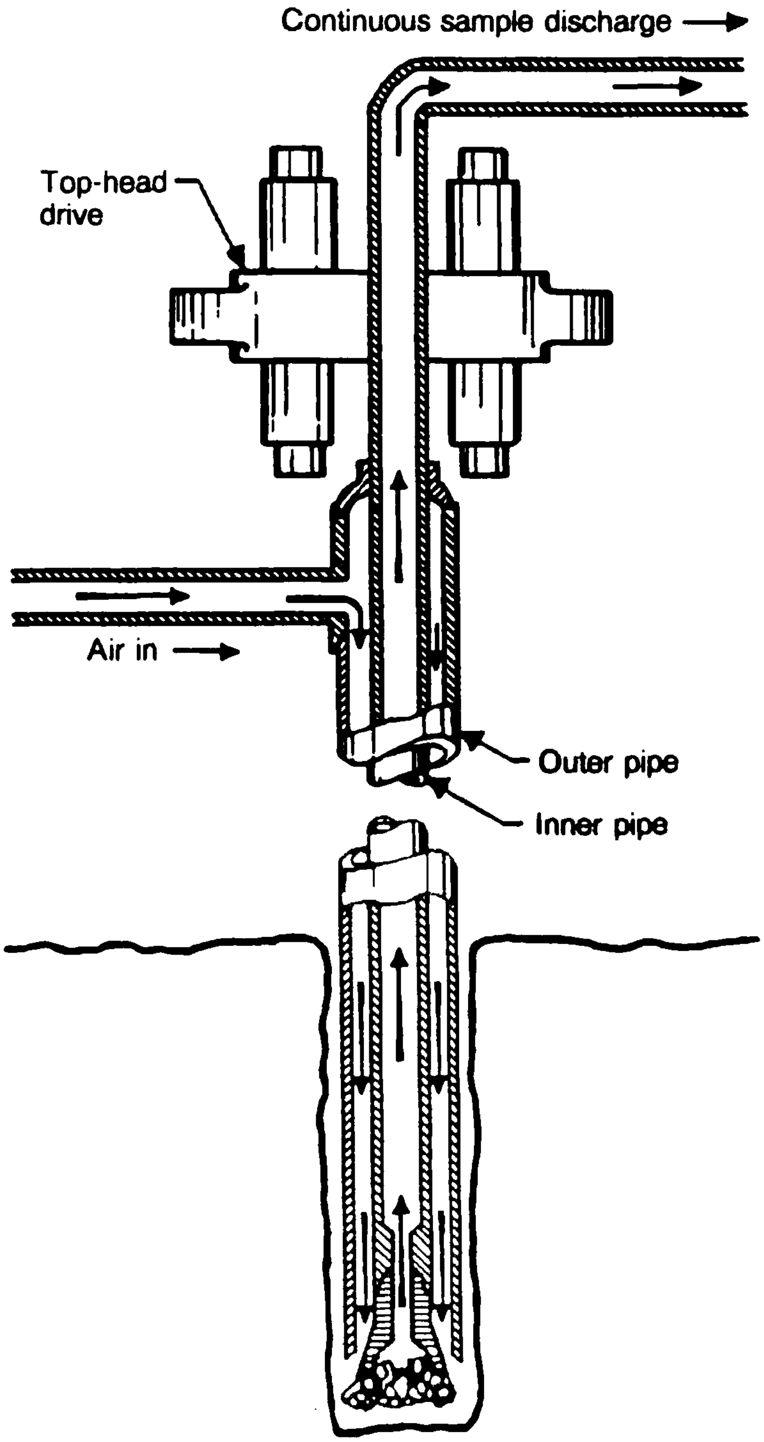
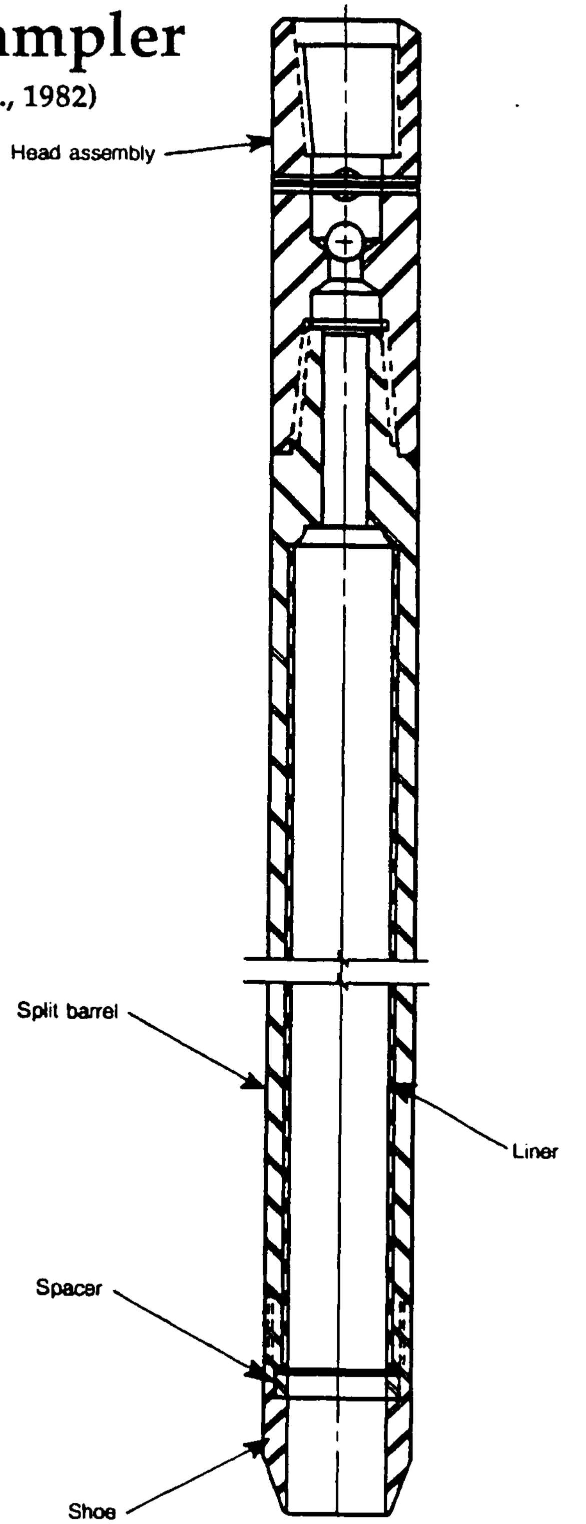


Diagram of a Split-Spoon (Split-Barrel) Sampler

(from Mobile Drilling Co., 1982)



Example of a Continuous Soil Sampling Tube System

(from Central Mine Equipment Co., 1987)

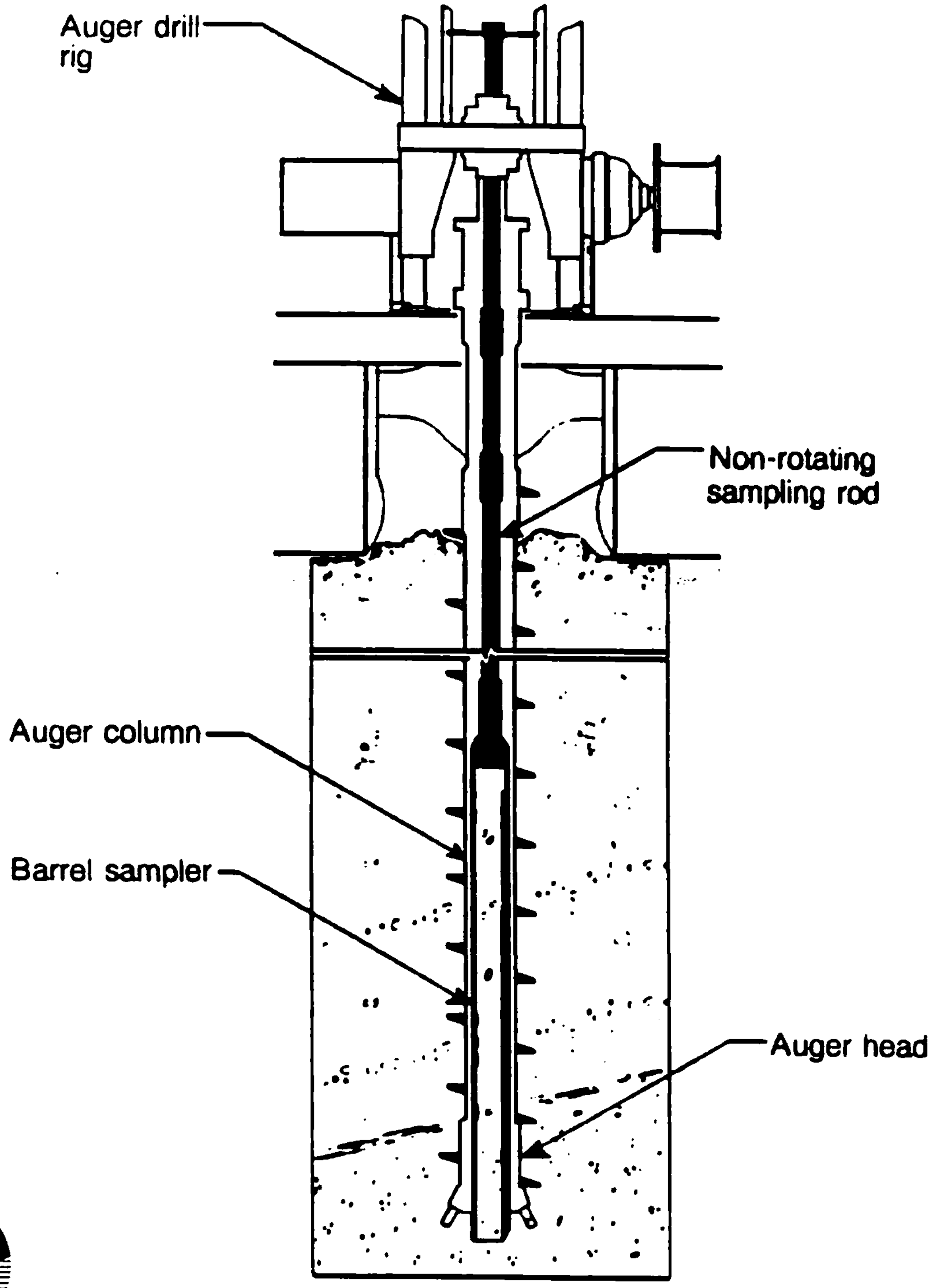
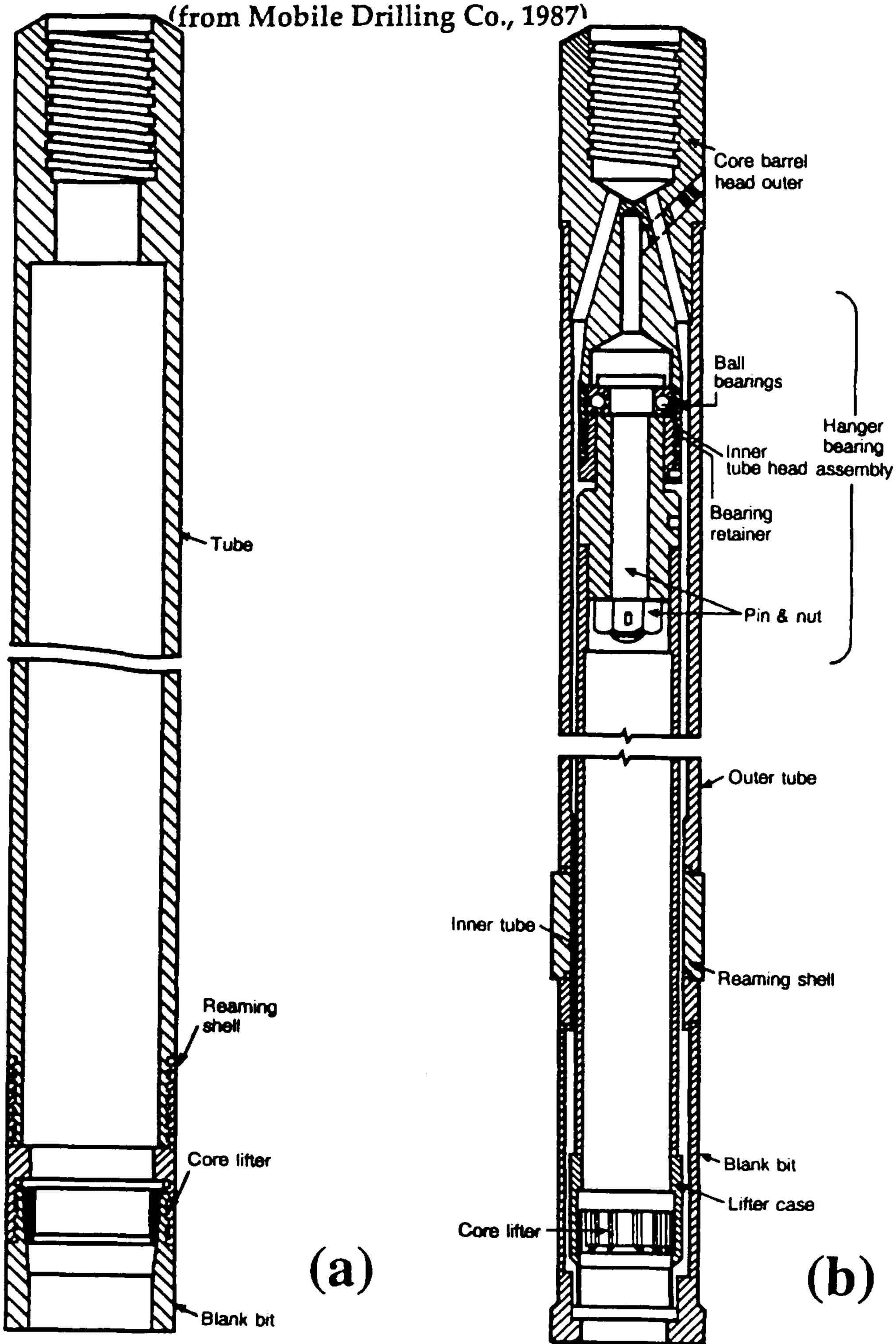


Diagram of Two Types of Core Barrels:

a) Single Tube and b) double-tube

(from Mobile Drilling Co., 1987)



ASTM D 2488
Checklist for Description of Soils

1	Group name
2	Group symbol
3	Percent of cobbles or boulders, or both (by volume)
4	Percent of gravel, sand, or fines, or all three (by dry weight)
5	Particle-size range: Gravel-fine, coarse Sand-fine, medium, coarse
6	Particle angularity: angular, subangular, subrounded, rounded
7	Particle shape: (if appropriate) flat, elongated, flat and elongated
8	Maximum particle size of dimension
9	Hardness of coarse sand and larger particles
10	Plasticity of fines: nonplastic, low medium, high
11	Dry strength: none, low medium, high, very high
12	Dilantancy: none, slow, rapid
13	Toughness: low medium, high
14	Color (in moist condition)
15	Odor (mention only if organic or unusual)
16	Moisture: dry, moist, wet
17	Reaction with HCl: none, weak, strong
	For intact samples:
18	Consistency (fine-grained soils only): very soft, soft, firm, hard, very hard
19	Structure: stratified, laminated, fissured, slickensided, lensed homogeneous
20	Cementation: weak, moderate, strong
21	Local name
22	Geologic interpretation
23	Additional comments: presence of roots or root holes, presence of rust, gypsum, etc., surface coatings on coarse-grained particles, cavings, sloughing of auger hole or trench sides, difficulty in augering or excavating, etc.

Suggested Minimum Soil Description Checklist

Experience indicates that geologists do not follow this checklist methodically. A simple, common-sense checklist is presented below for use consistency in field work. Its emphasis is to describe the soil relative to defining the presence and/or the conditions of the potential transport pathways of hazardous materials through soils & groundwater.

e.g. - SAND with Silt: light brown, fine to coarse sand, subrounded, coarse silt, angular moderately sorted, moist, none-HCl, presence of roots, hard drilling, compact (SM)

1 Soil name - e.g., SAND with Silt (primary particle size is sand, secondary is silt - in this order)
and, with, and some - in the name provides an indication of relative proportions.
and indicates 45 to 30 percent of volume
with indicates 30 to 15 percent of volume
some indicates 15 to 5 percent of volume
(Use of the name "Silty SAND" is ambiguous on volume of silt in sample.)

2 Color - e.g., light brown
Munsell color chart name and code should be used for description

3 Particle-size range of primary - e.g., fine to coarse sand

4 Angularity/Roundness of primary particles - e.g., subrounded

5 Particle-size range of secondary - e.g., coarse silt

6 Angularity/Roundness of secondary particles - e.g., angular

7 Sorting - e.g., moderately sorted

8 Moisture - e.g., moist

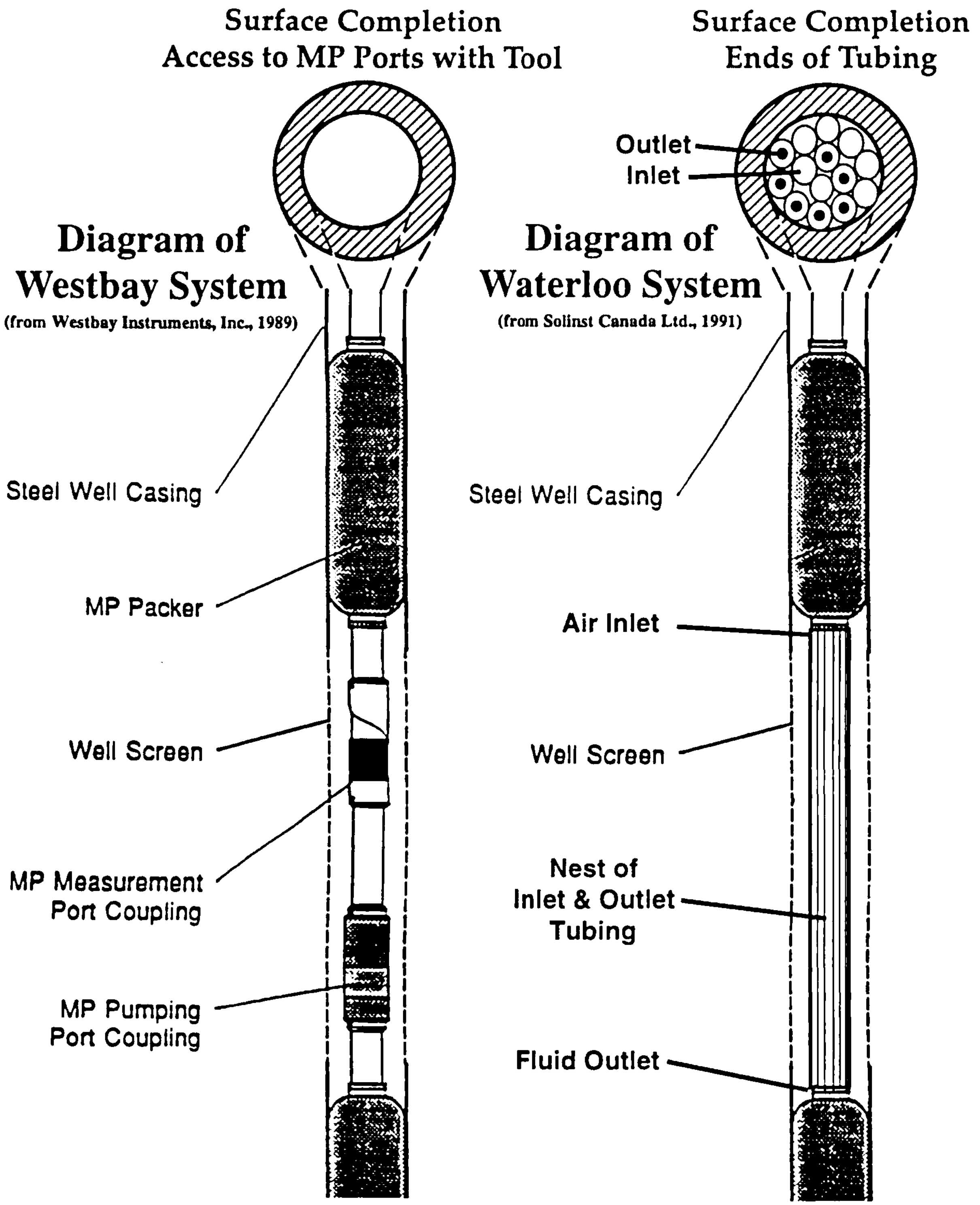
9 Reaction with HCl - e.g., none-HCl

10 Miscellaneous - e.g., presence of roots, hard drilling, compact

11 USCS Code - e.g., (SM)

Subsurface Geophysical Logging Tool Use Chart

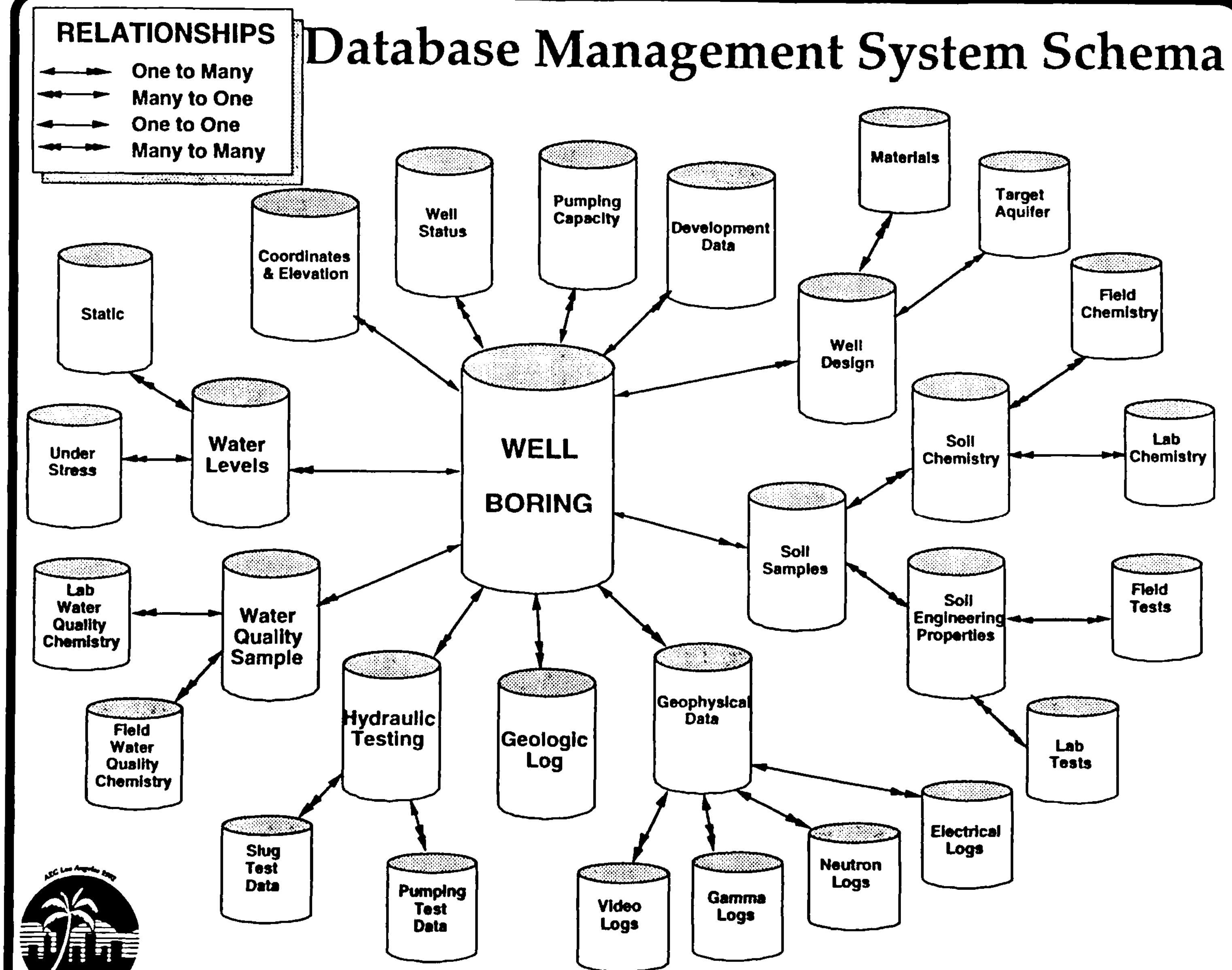
Tool Uses \ Tools	T.V.-3D	Resis-tivity	S.P.	Caliper	Flow-meter	Temp-erature	Gamma Ray	Neutron	Density	Salinity
Bed Boundaries (Thickness)	❑	❑	❑				❑	❑	❑	
Borehole Diameter or Casing Size				❑						
Cement Top Location						❑	❑			
Correlation		❑	❑				❑	❑	❑	
Damaged Casing Location	❑			❑						
Density (Bulk)									❑	
Depth Control	❑	❑	❑				❑	❑		
Fluid Content		❑				❑		❑	❑	
Fluid Movement Detection	❑				❑	❑				
Fluid Type		❑	❑					❑		
Formation Resistivity		❑								
Formation Water Salinity		❑	❑							❑
Injection Profiles					❑	❑				
Lithology		❑	❑				❑		❑	
Locate Fish	❑	❑								
Lost Circulation Zone Identification					❑	❑				
Moisture Content		❑						❑		
Permeable Zone Identification			❑	❑				❑		
Porosity		❑	❑					❑	❑	
Production Profiles					❑	❑				
Shale Content		❑	❑				❑	❑		
Temperature						❑				
Uranium Ore Grade							❑			
Water Level	❑	❑	❑		❑	❑		❑		



Simplified Diagrams of Multi-Port Sampling Well Techniques

Groundwater Monitoring and Remediation Techniques Short Course

Database Management System Schema



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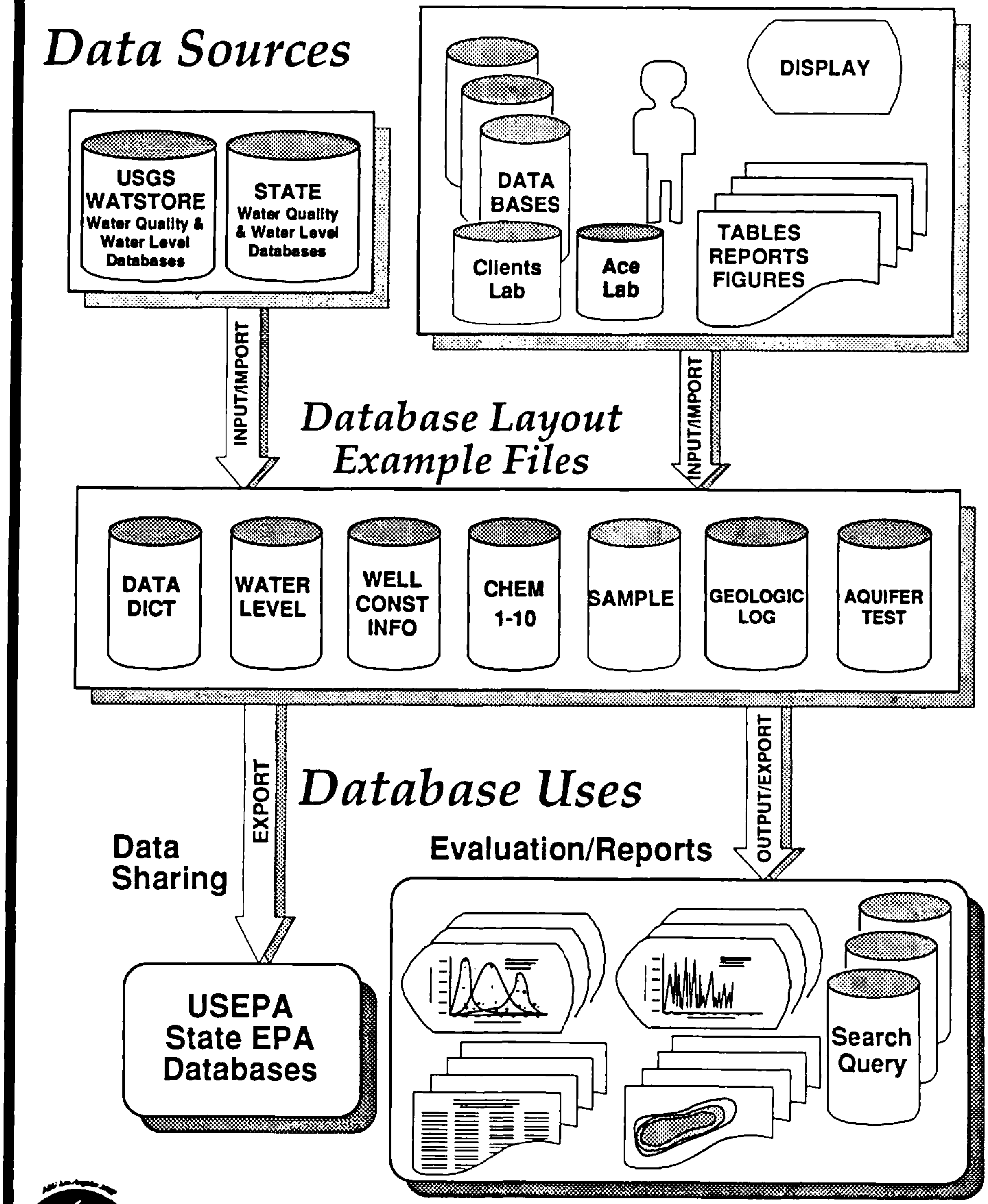

Database Management System Flowchart

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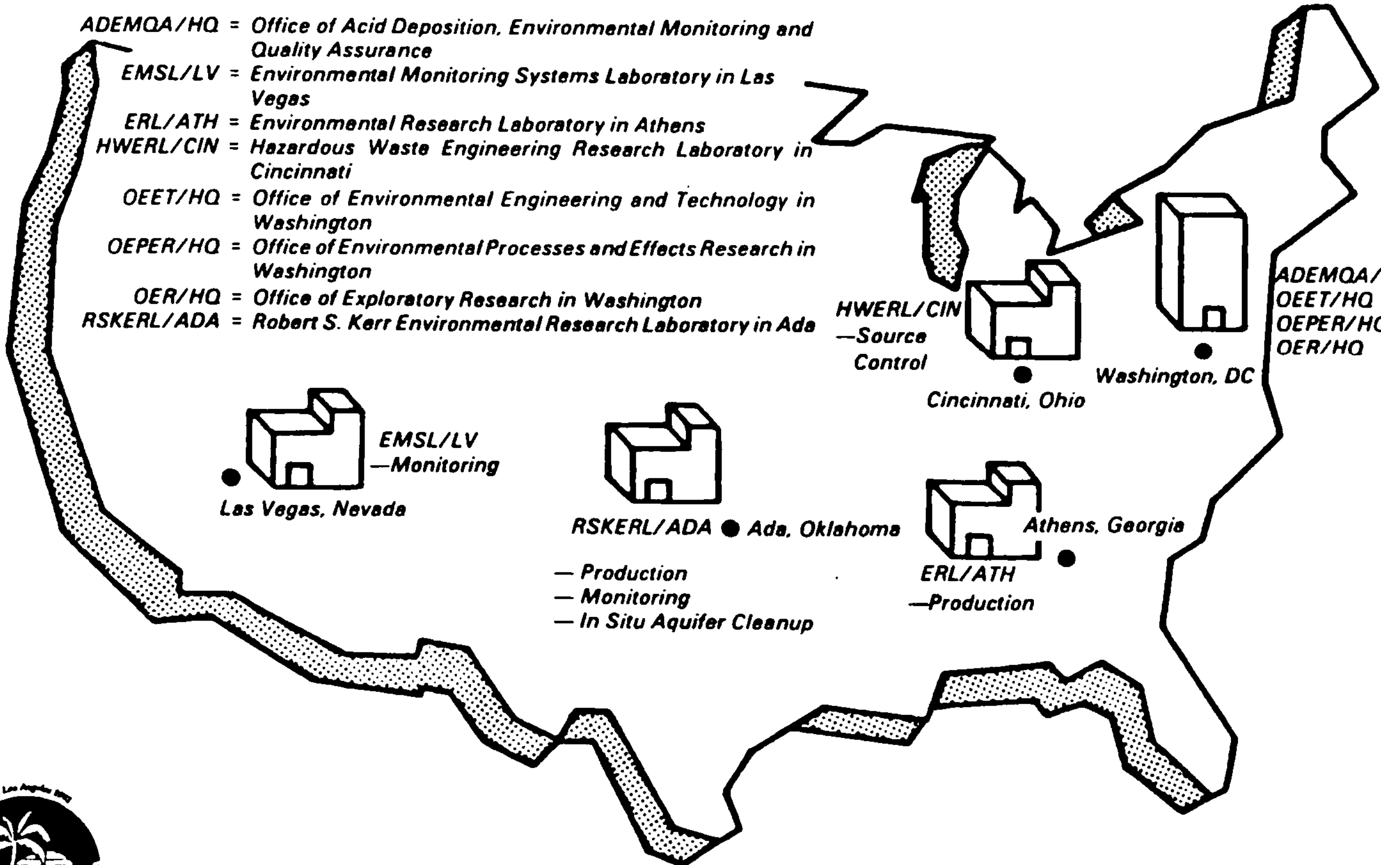
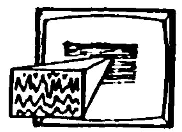
EPA Offices and Laboratories Involved in Groundwater Research Programs. Part of the Office of Research and Development

ADEMQA/HQ = Office of Acid Deposition, Environmental Monitoring and Quality Assurance
EMSL/LV = Environmental Monitoring Systems Laboratory in Las Vegas
ERL/ATH = Environmental Research Laboratory in Athens
HWERL/CIN = Hazardous Waste Engineering Research Laboratory in Cincinnati
OEET/HQ = Office of Environmental Engineering and Technology in Washington
OEPER/HQ = Office of Environmental Processes and Effects Research in Washington
OER/HQ = Office of Exploratory Research in Washington
RSKERL/ADA = Robert S. Kerr Environmental Research Laboratory in Ada



EPA Expert Systems and Environmental Software

Developed by
EPA Environmental Monitoring System Laboratory (EMSL) Las Vegas

	SYSTEM	FUNCTION AND FEATURES
	GeoEas	Performs geostatistical analysis on spatially-distributed environmental data. Includes kriging, graphics, and plotting capabilities.
	SCOUT	Assists in exploratory data analysis. Identifies multivariate outliers, determines the variable(s) in which the anomaly occurred, and displays the data set through interactive three-dimensional graphics.
$\sigma_T^2 = \sigma_S^2 + \sigma_A^2$	ASSESS	Calculates measurement errors for soil sampling based on results from appropriate quality assurance samples.
	Rationale for Assessing Errors in the Sampling of Soils	Explains a soil sampling quality assurance approach in a computerized document through the use of hypertext and provides access to the ASSESS software.

EPA Expert Systems and Environmental Software

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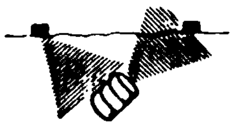
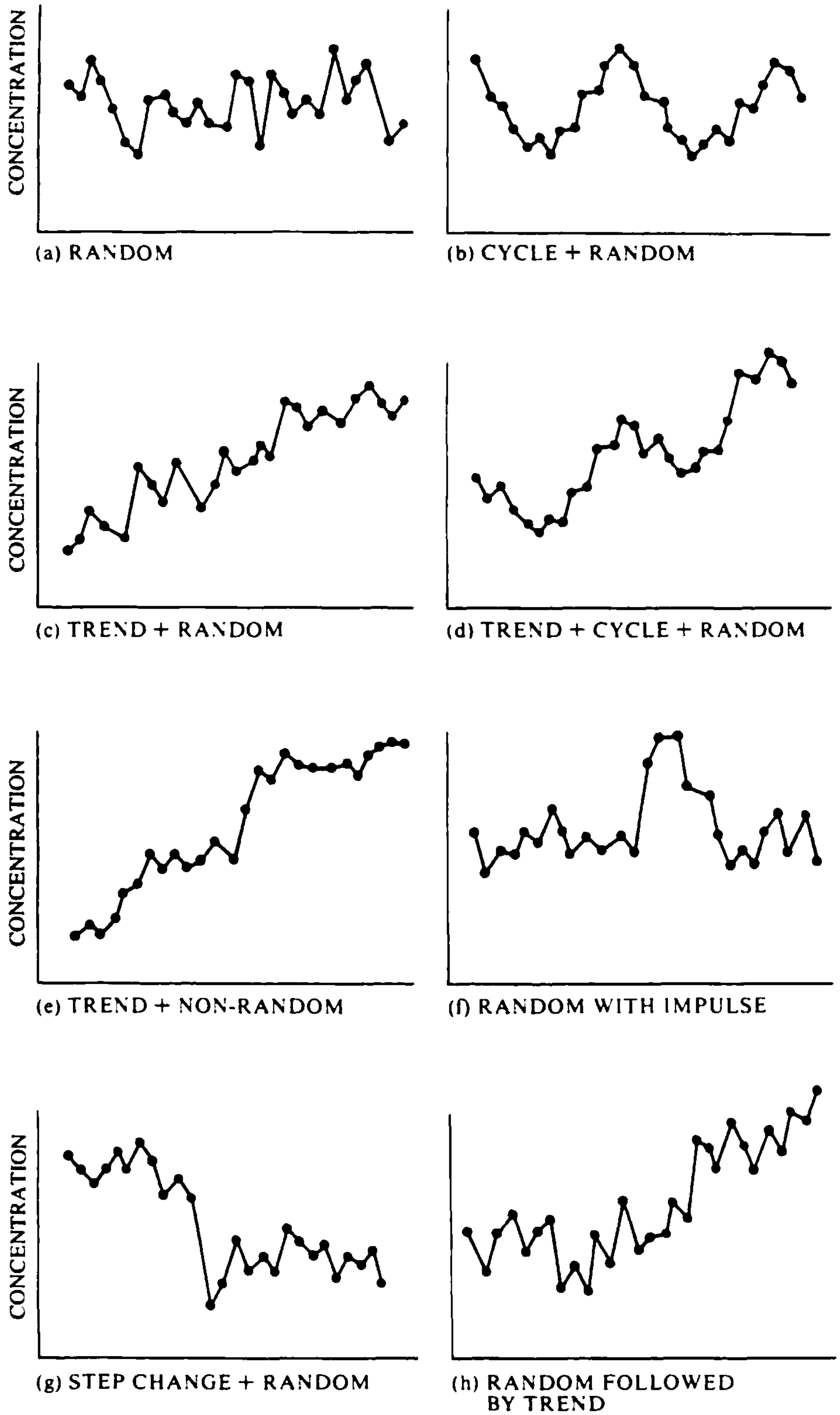
	SYSTEM	FUNCTION AND FEATURES
	**Geophysics Expert Advisor**	Provides assistance on the use of geophysical monitoring methodology for hazardous waste site assessments. Uses expert system techniques for method selection.
	**Environmental Sampling Expert System (ESES)**	Assists in preparation of field sampling plans to measure ground-water contamination and metal pollution in soil. Combines expert system and hypertext techniques for decision support and help.
	**Computer-Aided Data Review and Evaluation (CADRE)**	Performs semi-automated data validation for the Superfund Contract Laboratory Program multi-method analytical results.
	**Smart Method Index (SMI)**	Provides natural language access to various EPA analytical method and standard data bases.



Types of Time Series

(from Gilbert, 1987)

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[· ·] Shading = 1/2 Value of Non-Detected Concentration Value (Censored Data) for Selected Chemicals of Concern

Well Identification	Date	Al Aluminum	Sb Antimony	As Arsenic	Ba Barium	Be Beryllium	Cd Cadmium	Ca Calcium	Cr Chromium	Co Cobalt	Cu Copper	Fe Iron	Pb Lead	Mg Magnesium	Mn Manganese	Hg Mercury	Ni Nickel	K Potassium	Se Selenium	Ag Silver	Na Sodium	Th Thallium	V Vanadium	Zn Zinc
6-S-02	10/12/81	429	40	4.10	27	0.50	1.50	30600	2.5	1.50	1.50	846	0.54	23400	54	0.10	8	2130	[illegible]	2	15800	1.5	3	244
6-S-03	10/24/81	383	40	2.30	13	0.50	3.20	28000	2.5	1.50	1.50	634	6.40	22100	66	0.10	8	2150	[illegible]	2	18300	1.5	3	313
6-S-01	08/19/81	1710	22	6.30	20	0.50	1.50	14700	44.5	12.80	80.70	4220	40.20	8870	186	0.10	22	2380	[illegible]	2	12800	1.5	14	386
6-S-05	03/07/81	7860	17.5	7.10	34	0.50	1.00	28600	64.8	6.50	14.20	6480	4.60	16400	88	0.10	22.4	3230	1.5	4	16300	1.5	16	38
2-MW-88	03/06/82	610	20	7.80	60	1.00	2.00	41300	4.5	6.00	8.50	813	1.40	75300	182	0.05	8	27900	2.3	4	47800	1	4	182
N14-15	01/29/82	2380	20	6.80	52	1.00	2.00	37600	4.5	2.50	8.80	3160	14.90	48800	312	0.20	12.8	5130	[illegible]	5	106000	1	10	28.8
4-MW-03	01/27/82	746	20	7.20	62	1.00	2.50	62300	2.50	2.50	1.00	861	6.30	47100	179	0.20	15.1	13700	[illegible]	5	80000	1	12.3	176
30-MW-01	03/05/82	760	1.55	3.60	46	1.00	2.00	38200	5.00	5.00	3.50	1000	0.50	41700	117	0.05	8.0	5610	[illegible]	5.0	85700	1	4	232
N29-21	03/20/82	30600	1.40	17.40	206	1.00	2.00	50600	60.0	15.00	70.00	38700	9.60	86400	710	0.05	106	16300	[illegible]	5.0	64200	1	66	80
MW-18-22	03/25/82	48600	22	18.80	431	3.40	2.00	34400	103.0	102	125.00	68800	35.80	48600	2520	0.31	342	6180	[illegible]	5	42500	1	146	301
Censored Data		0%	80%	0%	80%	80%	80%	0%	50%	70%	40%	0%	30%	0%	0%	70%	50%	0%	80%	100%	0%	100%	40%	10%
Minimum		383	1.55	2.30	13	0.50	1.00	14700	3	2.50	4	634	1	8870	54	0.05	8	2130	0.5	2	12800	1	3	38
Maximum		48600	38.00	18.80	431	3.40	3.20	62300	103	102.00	123	68800	40	86400	2520	0.31	342	27900	2.3	5	106000	2	146	386
Sum		88886	164.80	81.30	617	16.40	28.30	357600	290	166.40	351	122043	121	418479	4430	1.25	563	84610	10.3	30	468200	12	380	1870
Mean		8889	16.48	8.13	57	1.64	2.83	35760	30	16.64	35	12204	12	41847	443	0.12	56	8461	1.0	3	46820	1	37	187
Std Deviation		14893	10.27	5.20	1	0.82	0.36	10472	34	28.71	42	21494	14	23711	716	0.08	100	7975	0.5	1	28709	0	42	122

Sorted Analytical Values in Ascending Order

	Al Aluminum	Sb Antimony	As Arsenic	Ba Barium	Be Beryllium	Cd Cadmium	Ca Calcium	Cr Chromium	Co Cobalt	Cu Copper	Fe Iron	Pb Lead	Mg Magnesium	Mn Manganese	Hg Mercury	Ni Nickel	K Potassium	Se Selenium	Ag Silver	Na Sodium	Th Thallium	V Vanadium	Zn Zinc
	383	1.55	2.30	13	0.50	1.00	14700	2.5	1.50	1.50	634	0.54	8870	54	0.05	8	2130	0.5	2	12800	1	3	28.8
	429	9.7	3.60	20	0.50	1.50	28000	2.5	1.50	1.50	813	1.00	16400	66	0.05	8	2150	0.5	2	15800	1	3	38
	610	7.8	4.10	27	0.50	1.50	28600	2.5	5.00	5.00	846	1.40	22100	88	0.05	8	2380	[illegible]	2	16300	1	4	80
	746	17.5	6.30	34	0.50	2.00	30600	4.5	6.00	6.00	861	4.60	23400	117	0.10	8	3230	[illegible]	2	18300	1	4	176
	760	20	6.80	46	1.00	2.00	34400	4.5	6.00	8.00	1000	6.30	41700	179	0.10	12.8	5130	[illegible]	4	47800	1	10	182
	1710	20	7.10	52	1.00	2.00	37600	6.0	6.00	8.50	3160	6.40	47100	186	0.10	15.1	5610	[illegible]	5	80000	1	12.3	232
	2380	22	7.20	60	1.00	2.00	38200	44.5	8.50	18.20	4220	6.80	48800	182	0.10	22.0	6180	[illegible]	5	64200	1.5	14	244
	7860	22	7.80	62	1.00	2.50	41300	64.5	12.80	70.00	6480	14.90	48800	312	0.20	22.4	13700	[illegible]	5	85700	1.5	16	313
	30600	40	17.40	206	1.00	2.50	50600	68.0	16.00	80.70	38700	35.80	75300	710	0.20	106	16300	1.5	5.0	67800	1.5	66	301
	48600	40	18.80	431	3.40	3.20	62300	103.0	102	123.00	68800	40.20	86400	2520	0.31	342	27900	2.3	5.0	106000	1.5	146	386
Minimum	383	1.55	2.30	13	0.50	1.00	14700	2.50	2.50	3.50	634	0.50	8870	54	0.05	8	2130	0.50	2.00	12800	1.00	3.00	38
Maximum	48600	38.00	18.80	431	3.40	3.20	62300	103.00	102.00	123.00	68800	40.20	86400	2520	0.31	342	27900	2.30	5.00	106000	1.50	146.00	386
Sum	88886	164.80	81.30	646	16.40	28.30	357600	286.70	166.40	350.60	122043	120.70	418470	4430	1.25	563	84610	10.30	30.00	468200	12.00	380.30	1870
Mean	8889	16.48	8.13	65	1.64	2.83	35760	28.67	16.64	35.06	12204	12.07	41847	443	0.12	56	8461	1.03	3.00	46820	1.20	38.03	187
Std Deviation	8820	9.80	4.11	55	0.35	0.46	9382	35.86	4.05	32.86	10866	10.47	19730	191	0.06	28	4801	0.31	1.20	22073	0.24	16.20	100
Coefficient Var	1.03	0.80	0.51	0.50	0.24	0.22	0.26	0.96	0.24	0.94	0.89	0.87	0.47	0.43	0.46	0.53	0.50	0.31	0.40	0.46	0.20	0.61	0.56

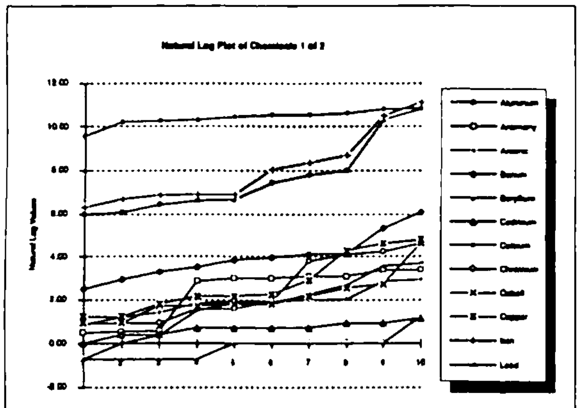
Logarithmic Expression of Analytical Data in Ascending Order

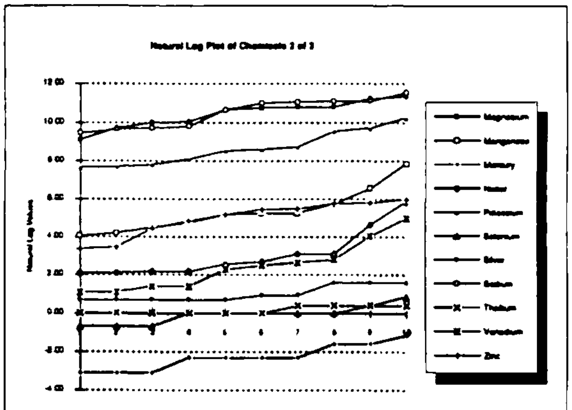
	Al Aluminum	Sb Antimony	As Arsenic	Ba Barium	Be Beryllium	Cd Cadmium	Ca Calcium	Cr Chromium	Co Cobalt	Cu Copper	Fe Iron	Pb Lead	Mg Magnesium	Mn Manganese	Hg Mercury	Ni Nickel	K Potassium	Se Selenium	Ag Silver	Na Sodium	Th Thallium	V Vanadium	Zn Zinc
	5.97	0.50	0.83	2.53	-0.69	0.00	9.60	0.92	0.92	1.26	6.29	-0.60	9.09	4.00	-3.10	2.08	7.66	-0.69	0.69	9.46	0.00	1.10	3.36
	6.06	0.53	1.25	2.97	-0.69	0.41	10.25	0.92	0.92	1.25	6.70	0.00	9.71	4.19	-3.10	2.08	7.67	-0.69	0.69	9.67	0.00	1.10	3.47
	6.41	0.56	1.41	3.31	-0.69	0.41	10.26	0.92	1.70	1.70	6.66	0.34	10.00	4.44	-3.10	2.20	7.77	-0.69	0.69	9.69	0.00	1.39	4.42
	6.61	2.86	1.64	3.53	-0.69	0.69	10.30	1.61	1.70	2.14	6.80	1.50	10.06	4.76	-2.30	2.20	8.08	0.00	0.69	9.81	0.00	1.39	4.84
	6.63	3.00	1.90	3.81	0.00	0.69	10.46	1.61	1.79	2.15	6.91	1.84	10.64	5.18	-2.30	2.56	8.54	0.00	0.69	10.66	0.00	2.30	5.20
	7.44	3.00	1.96	3.95	0.00	0.69	10.53	1.83	1.79	2.25	8.06	1.86	10.76	5.24	-2.30	2.71	8.61	0.00	0.92	11.00	0.00	2.51	5.46
	7.77	3.09	1.97	4.06	0.00	0.69	10.54	3.80	2.14	2.90	8.35	1.92	10.79	5.29	-2.30	3.09	8.73	0.00	0.92	11.07	0.41	2.64	5.50
	7.89	3.09	2.00	4.12	0.00	0.92	10.63	4.07	2.56	4.28	8.70	2.70	10.81	5.74	-1.61	3.11	9.53	0.00	1.61	11.09	0.41	2.77	5.75
	10.33	3.37	2.86	5.33	0.00	0.92	10.83	4.22	2.71	4.36	10.51	3.58	11.23	6.57	-1.61	4.66	9.70	0.41	1.61	11.12	0.41	4.09	5.80
	10.81	3.37	2.94	6.07	1.22	1.16	10.96	4.63	4.62	4.81	11.14	3.69	11.36	7.83	-1.17	5.83	10.24	0.83	1.61	11.56	0.41	4.98	5.96
Minimum	5.97	0.50	0.83	2.53	-0.69	0.00	9.60	0.92	0.92	1.25	6.29	-0.60	9.09	4.00	-3.10	2.08	7.66	-0.69	0.69	9.46	0.00	1.10	3.36
Maximum	10.81	3.37	2.94	6.07	1.22	1.16	10.96	4.63	4.62	4.81	11.14	3.69	11.36	7.83	-1.17	5.83	10.24	0.83	1.61	11.56	0.41	4.98	5.96
Sum	76.86	23.38	18.83	38.67	-1.54	6.54	104.33	24.62	20.96	27.40	80.38	17.06	104.44	63.31	-22.90	30.61	88.54	-0.64	10.13	105.15	1.62	24.23	49.76
Mean	7.69	2.34	1.88	3.87	-0.15	0.65	10.43	2.46	2.09	2.74	8.04	1.71	10.44	6.33	-2.29	3.06	8.85	-0.06	1.01	10.51	0.16	2.42	4.98
Stand Dev	1.82	1.19	0.62	1.09	0.56	0.31	0.34	1.46	1.01	1.29	1.54	1.28	0.64	1.09	0.64	1.18	0.89	0.47	0.40	0.73	0.20	1.23	0.90

		Al Aluminum	Sb Antimony	As Arsenic	Ba Barium	Be Beryllium	Cd Cadmium	Ca Calcium	Cr Chromium	Co Cobalt	Cu Copper	Fe Iron	Pb Lead	Mg Magnesium	Mn Manganese	Hg Mercury	Ni Nickel	K Potassium	Se Selenium	Ag Silver	Na Sodium	Th Thallium	V Vanadium	Zn Zinc
Lognormally Distributed	d values	38.78	14.20	3.83	10.02	3.18	0.96	1.17	21.08	10.24	16.33	25.10	10.38	4.64	11.86	4.15	14.03	7.42	2.25	1.60	5.36	0.39	15.06	6.06
	W Calculated	0.838	0.888	0.931	0.931	0.787	0.838	0.888	0.829	0.861	0.888	0.886	0.852	0.838	0.900	0.886	0.782	0.911	0.882	0.703	0.883	0.640	0.888	0.871
	90%ile from Ecology Table A-2	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842	0.842
W - 90%ile Table A-2 = Lognormal Dist ?		-0.003	-0.144	0.089	0.089	-0.08	0.084	0.047	-0.014	0.009	0.027	0.023	0.110	0.087	0.058	0.044	-0.060	0.089	0.080	-0.14	0.021	-0.202	0.047	0.029
	90%ile Ln Value	9.082	3.864	2.886	6.351	0.660	1.064	10.871	4.394	3.394	4.379	10.070	3.480	11.310	6.733	-1.464	4.606	9.758	0.521	1.53	11.462	0.417	3.896	6.139
90%ile Potential Cleanup Std. (ug/l)		10025	48	16	181	1.76	2.87	52926	75	30	80	23621	33	81647	839	0.23	88	17294	1.68	5	94106	1.52	54	464
MTCA B Groundwater Carcinogen-Carc Std (ug/l)		N/A	6.4	0.05	1120	0.020	8	N/A	80	N/A	592	N/A	16	N/A	528	4.80	320	N/A	N/A	48	N/A	1.12	112	3200
90%ile Level/Method B Level - Ratio		N/A	7	295	0.170	87	0.359	N/A	0.94	N/A	0.135	N/A	2.2	N/A	1.6	0.048	0.302	N/A	N/A	0.096	N/A	1.364	0.485	0.143
80 %ile Level (ug/l)		3006	10	7	63	0.86	1.83	33948	11.73	8.05	15.48	3098	5.52	34362	207	0.10	21	5732	0.87	3	38847	1.18	11	146
4 x 80%ile-Potential Carc Cleanup Std. (ug/l)		8032	41	27	211	3.43	7.72	135782	46.93	32.20	61.98	12394	22.08	137406	827	0.40	86	22930	3.66	11	147387	4.70	46	580
	P Values Calculated	0.864	1.163	2.243	1.385	2.460	4.40	4.053	0.864	1.390	1.086	0.875	0.996	2.053	1.368	2.151	1.170	1.610	2.836	3.47	1.886	0.978	1.130	1.544
%ile of (4 x 80%ile) Cleanup Level (P in Tbl A-9)		80.4	87.78	98.75	91.7	99.31	100.00	100.00	83.94	91.46	85.10	80.80	84.80	98.00	89.76	98.42	87.80	94.63	99.84	99.97	97.10	100.00	87.08	93.88
90 %ile (ug/l) - 4 x80%ile (ug/l) =		7994	6	-12	-21	-1.68	-5	-83164	28	-2.71	18	11227	11	-55761	13	-0.17	12	-5638	-1.99	-6.42	-53282	-3.19	8	-121

Pb 15 ug/l EPA AL

Normally Distributed	Al Aluminum	Sb Antimony	As Arsenic	Ba Barium	Be Beryllium	Cd Cadmium	Ca Calcium	Cr Chromium	Co Cobalt	Cu Copper	Fe Iron	Pb Lead	Mg Magnesium	Mn Manganese	Hg Mercury	Ni Nickel	K Potassium	Se Selenium	Ag Silver	Na Sodium	Th Thallium	V Vanadium	Zn Zinc
Normal 80 %ile Level (ug/l)	9000	17	8	88	1.36	2.31	35750	31	17	38	12286	13	41848	444	0.71	56	8482	1.42	3.51	46821	1.46	38	188
Normal 80 %ile Level/Method B Level	N/A	3	175	0.08	86	0.29	N/A	0	N/A	0.06	N/A	N/A	N/A	0.84	0.15	0.16	N/A	N/A	0.07	N/A	1.30	0.25	0.06
Normal 80 %ile (ug/l)	8886	17	8	85	1.34	2.21	35760	31	17	35	12286	13	41847	443	0.51	56	8461	1.39	3.34	46820	1.37	37	187
Normal 80%ile Level/Method B Level	N/A	3	171	0.08	81	0.29	N/A	0	N/A	0.06	N/A	N/A	N/A	0.84	0.11	0.17	N/A	N/A	0.07	N/A	1.27	0.25	0.06
80%ile Non-Parametric Values (ug/l)	34680	38	18	177	1.80	2.50	48730	68	15	94	30644	32	70160	630	0.20	88	15780	1.40	5.00	67220	1.50	60	327
80%ile Non-Paramet. Level/Method B Levels	N/A	4	309	0.16	48	0.21	N/A	1	N/A	0.16	N/A	N/A	N/A	1.19	0.04	0.29	N/A	N/A	0.10	N/A	1.34	0.44	0.10





Analytical Results and Statistical Evaluation of Selected Background Groundwater Samples from a Location in Washington State

Groundwater Monitoring and Remediation Techniques Short Course

Summary of Common Solution Techniques for Problems of Fluid Flow

Problem	Solution Technique	Description/Comments on the Method	Key References
Groundwater Flow	*Analytical*	Involves the use of classical mathematical techniques for solving differential equations. Widely used for more than 35 years in groundwater resources evaluation.	Hantush (1964) Jacob (1940) Kruesman and de Ridder (1983) Lohman (1979) Theis (1935) Walton (1970)
	Finite difference	Uses differential equations to approximate derivatives, resulting in a series of algebraic equations. Widely used since the 1960s with few limitations.	Mercer and Faust (1981) Remson et al. (1971) Wang and Anderson (1982)
	Finite element	Creates an integral form of the differential equation; again discretization provides a system of linear algebraic equations. Widely used with few limitations. The ability to use a variety of element shapes is helpful in subdividing irregularly shaped aquifer or geologic units.	Huyakorn and Pinder (1983) Mercer and Faust (1981) Pinder and Gray (1977) Zienkiewicz (1977)
	Boundary elements or boundary integral methods	Creates integral form of the governing flow equation relying on boundary rather than areal integrals. By working with the boundaries of aquifers or units this method avoids internal discretization, and thus a small number of large elements can be used instead of the finite-element method.	DeMarsily (1986) Liggett and Liu (1983)
Multiphase flow Unsaturated zone	*Analytical*	See above.	Lappala (1980) Nielsen et al. (1986)
	Finite Difference	See above; sharp changes in parameters at wetting front require consideration in grid design.	Hanks et al. (1969) Jeppson (1974) Narasimhan et al. (1978) Neuman (1972) Neuman and Narasimhan (1977) Pruess (1980) Reisenauer (1963)
	Finite element	See above.	Yeh and Ward (1980)
Two-fluid flow	*Finite difference*	See above; solves flow equation for each fluid	Abriola and Pinder (1985) Baehr and Corapcioglu (1987) Corapcioglu and Baehr (1987) Faust (1985)
	Finite element	See above.	Lenhard and Parker (1987) Osborne and Sykes (1986) Parker and Lenhard (1987)

(from National Academy of Sciences, 1990)

Summary of Common Solution Techniques for Problems of Dissolved Mass Transport

Problem	Solution Technique	Description/Comments on the Method	Key References
Dissolved contaminant transport	*Analytical*	See above; a variety of different solutions exists for contaminant transport in one, two, and three dimensions.	Cleary and Ungs (1978) Domenico and Robbins (1985) Jandeval et al. (1984) Ogata (1970) van Genuchten and Alves (1982)
	Finite difference	See above; in advection-dominated problems, numerical dispersion and oscillations can develop in solution. Case of multicomponent transport with reaction requires special consideration.	Reeves et al. (1986) Welch et al. (1966)
	Finite element	See above; same problems as finite difference.	Huyakorn and Pinder (1983) Voss (1984) Yeh and Ward (1981)
	Method of characteristics	Breaks the advection-dispersion equation into two parts, one accounting for advection and the other accounting for dispersion. Requires the transport of reference particles.	Bredehoeft and Pinder (1973) Konikow and Bredehoeft (1978) Reddell and Sunuda (1970)
	Random walk methods	One of the few techniques not involving a solution of the advection-dispersion equation. Simulates the migration of contaminants by moving a set of reference particles. Generally provides an approximate solution.	Ahlstrom et al. (1977) Prickett et al. (1981) Schwartz and Crowe (1980)

(from National Academy of Sciences, 1990)

General Capabilities of Popular Public Domain Groundwater Models

Codes	Dimensions		Processes			Numerics		Authors
	2D	3D	Flow	Transport	Unsat.	Finite Difference	Finite Element	
CFEST		●	●	●			●	Gupta et al
FEMWASTE	●			●	●		●	Yeh
FEMWATER	●		●		●		●	Yeh
HST3D		●	●	●		●		Kipp
MODFLOW		●				●		McDonald & Harbaugh
MT3D		●		●		●		Zheng
PLASM		●	●			●		Prickett & Lonquist
RANDOM WALK	●			●		●		Prickett et al
SUTRA	●		●	●	●		●	Voss
SWANFLOW		●	●		◆	●		Faust
SWIFT II		●	●	●		●		Reeves et al
USGS-2D	●					●		Trescott et al
USGS-MOC	●			●		●		Konikow & Bredehoeft

◆ *Immiscible Phase Flow*

Equilibrium Expressions for the Partitioning of Volatile Organic Chemicals among Aqueous, Vapor and Sorbed Phases

Unsaturated zone

$$K_p = \frac{\text{Conc.}_{Soil}}{\text{Conc.}_{Gas}}$$

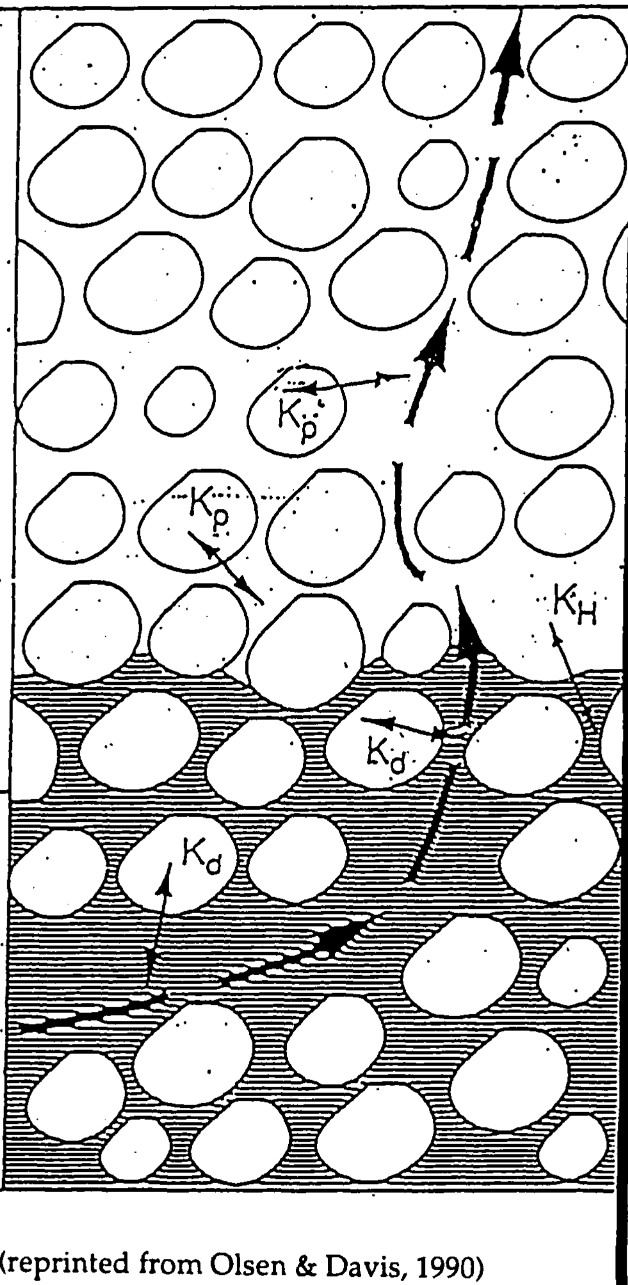
Capillary zone

$$K_H = \frac{\text{Conc.}_{Gas}}{\text{Conc.}_{Water}}$$

Saturated zone

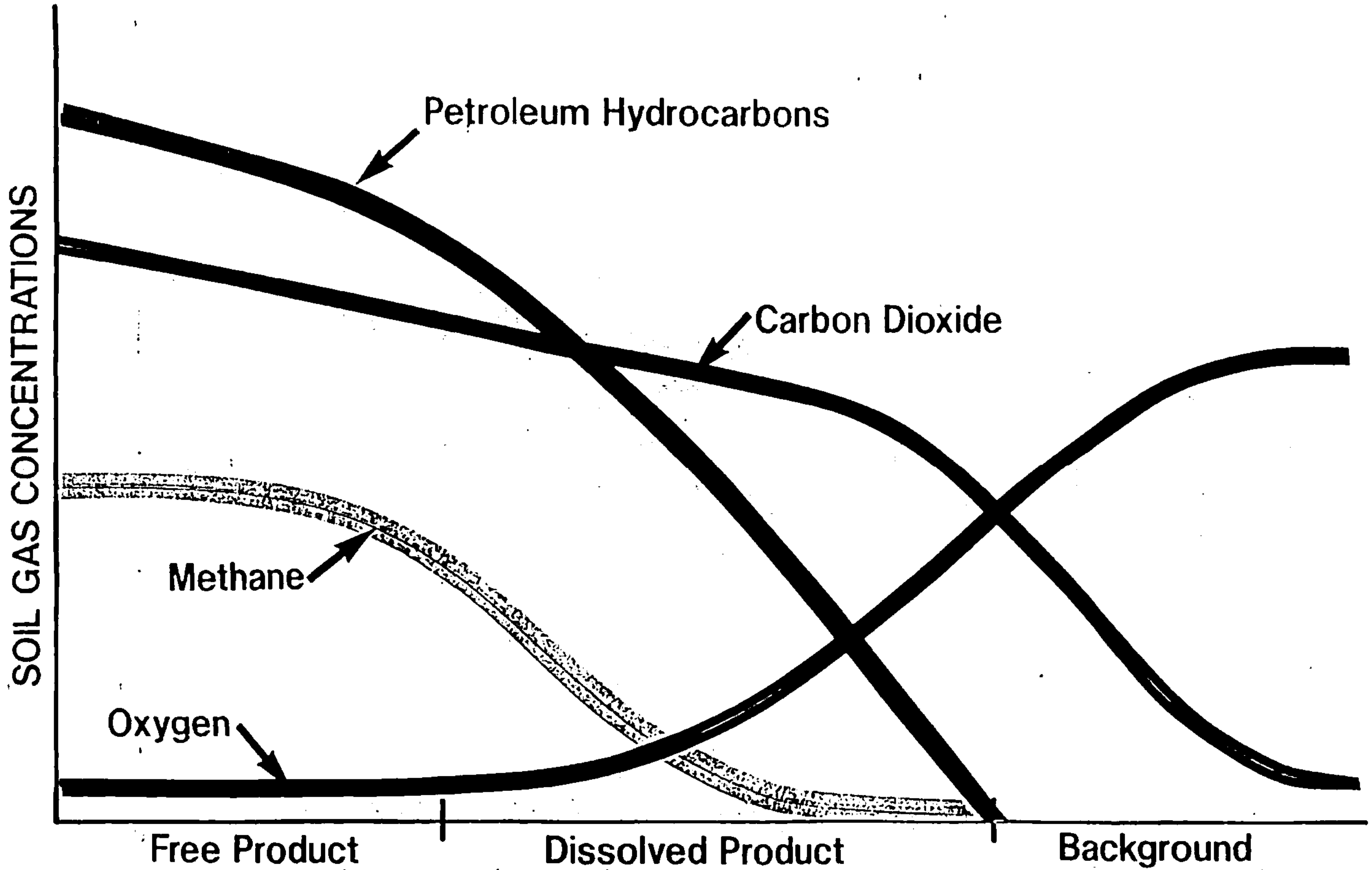
$$K_d = \frac{\text{Conc.}_{Soil}}{\text{Conc.}_{Water}}$$

Ground Water flow



(reprinted from Olsen & Davis, 1990)

(from Marrin, 1988)



Distance from Groundwater Source

Groundwater Monitoring and Remediation Techniques Short Course

Requirements for Calculation of Air Permeability

Radius and Screened Interval of Extraction Well

Flow Rate/Vacuum Pressure at Extraction Well

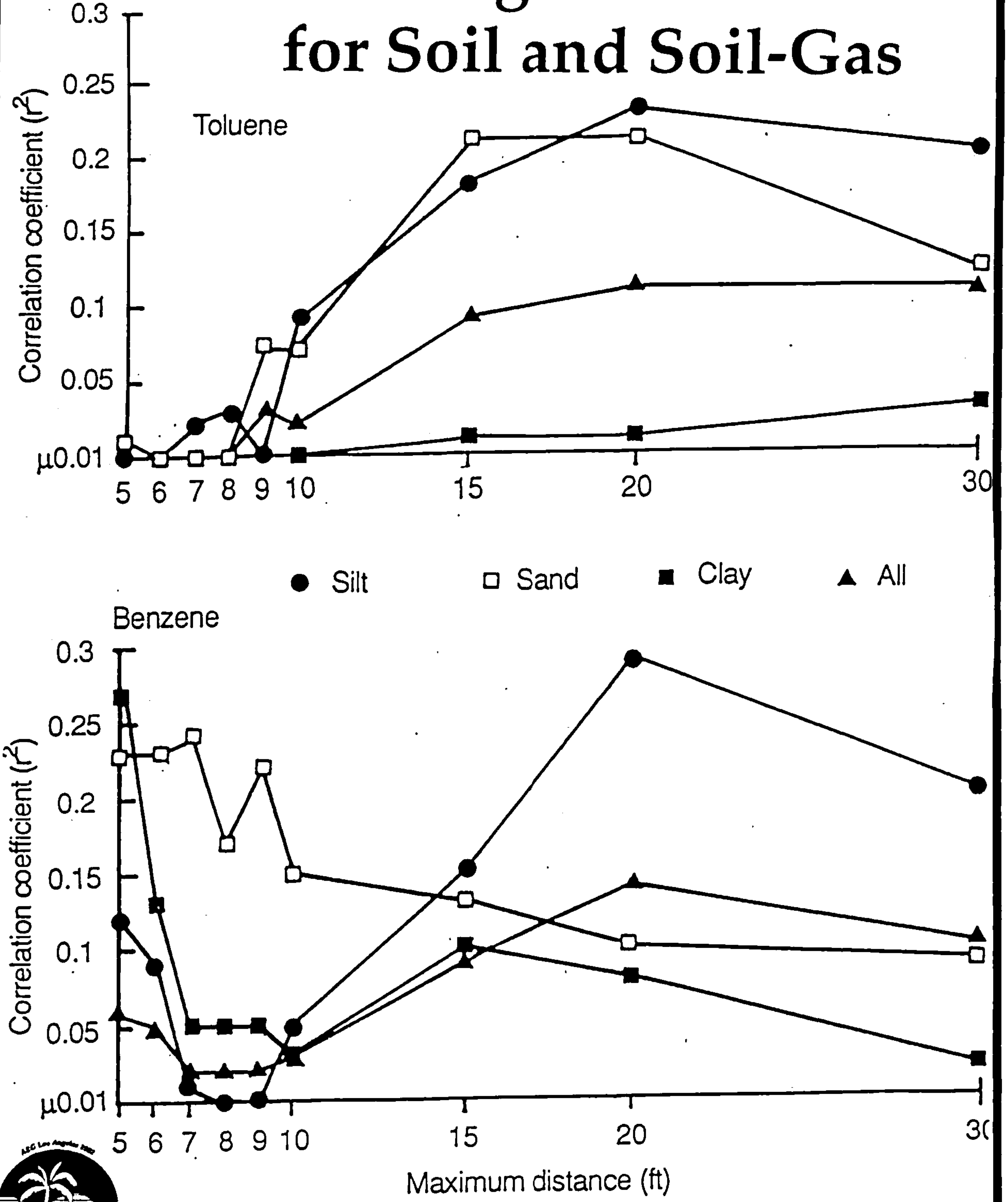
Vacuum Pressure at Observation Wells

Radius of Influence (*Pressure Definition*)

Physical Properties of Air

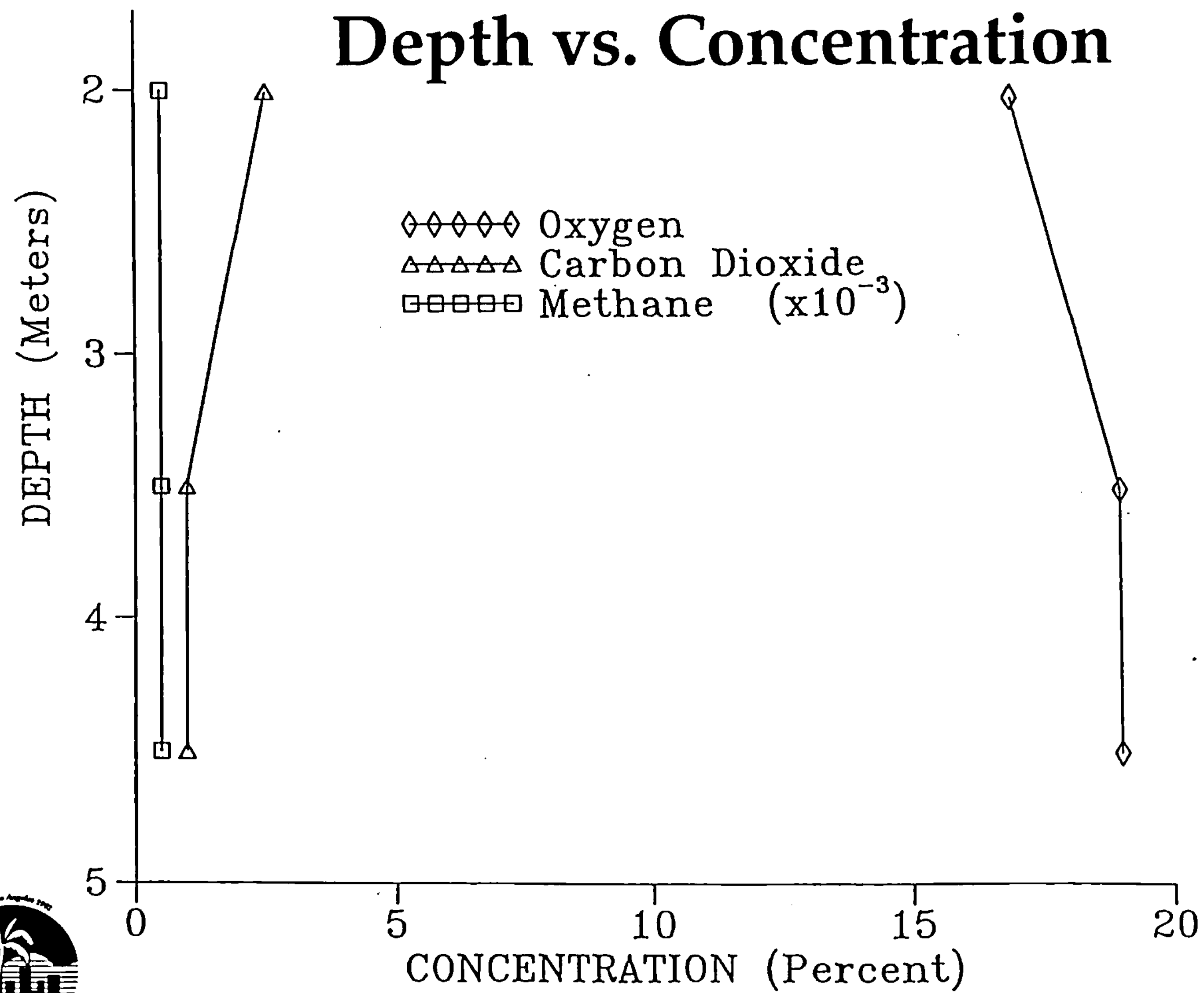
(from Marks & Singh, 1990)

Linear Regression Results for Soil and Soil-Gas



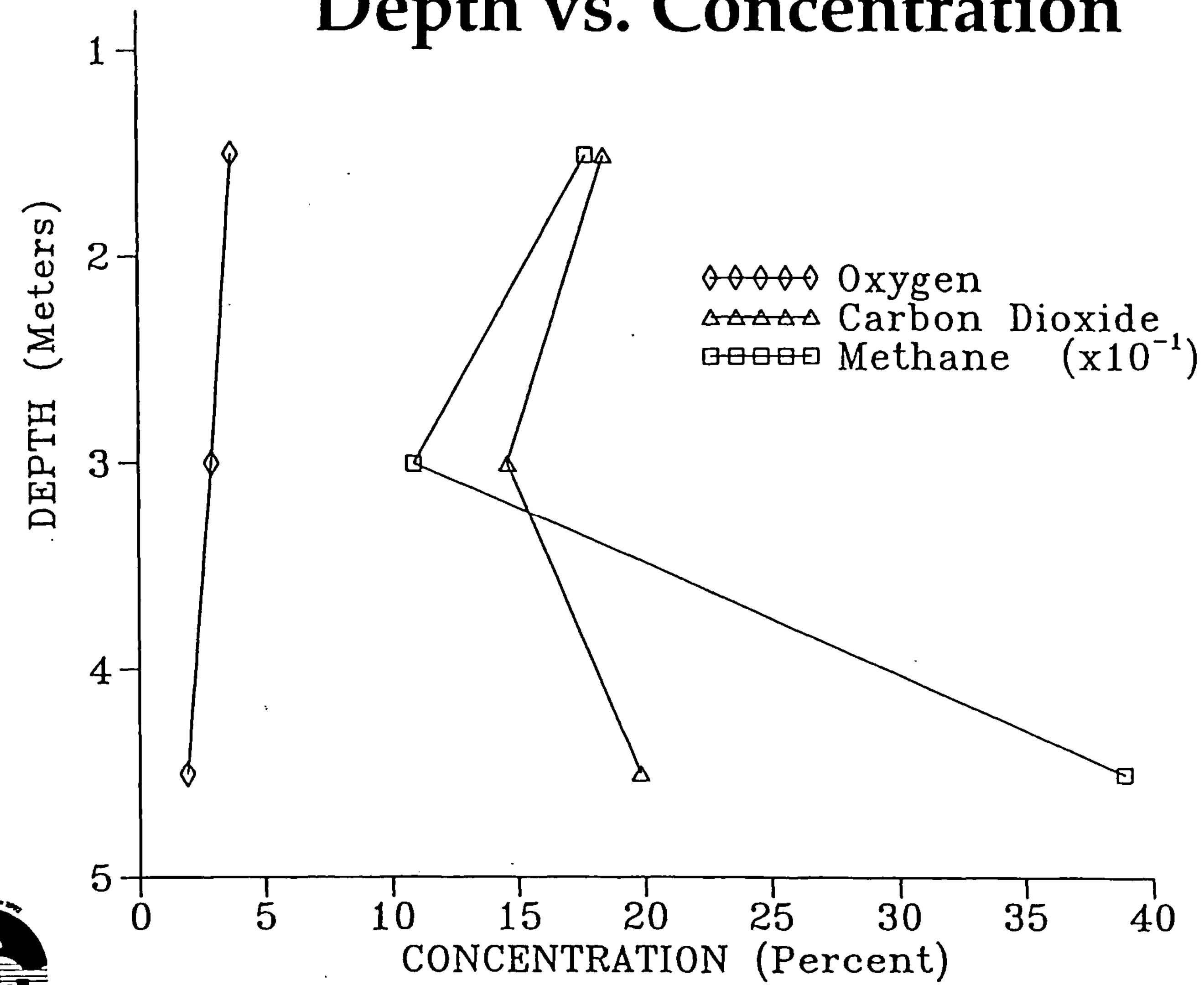
(from Marrin, 1991)

Depth vs. Concentration



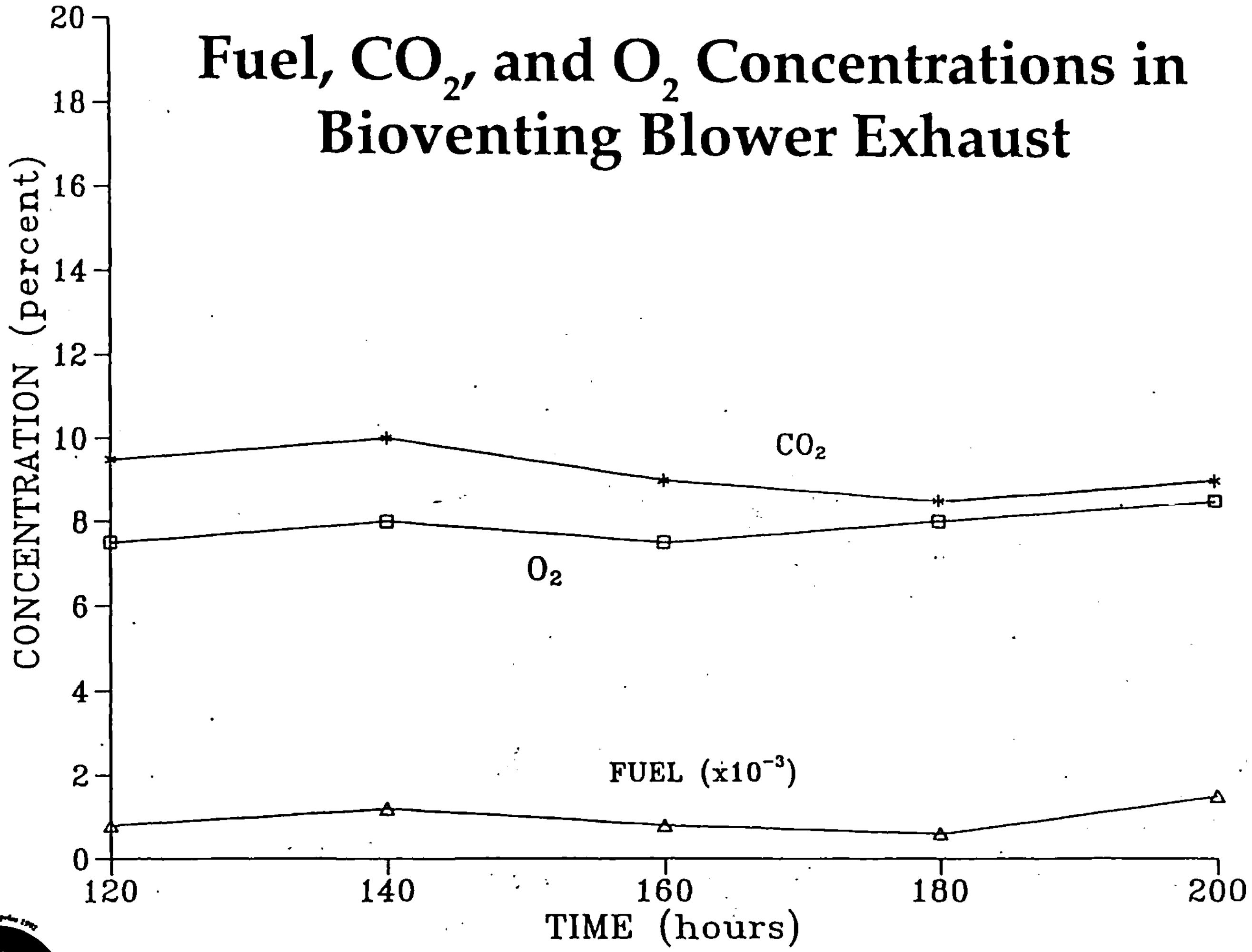
(from Marrin, 1991)

Depth vs. Concentration



(from Marrin, 1992)

Fuel, CO_2, and O_2 Concentrations in Bioventing Blower Exhaust



Applications for Soil Vapor Extraction

"Micro" Scale Validation of "Macro" Scale Techniques

Preliminary Calculations of Air Permeability

Prediction of Anisotropic Air Flow (*Vertical/Horizontal*)

Estimation of Soil->Vapor Partitioning of Contaminants

Indication of Kinetically-Controlled Processes

Provide a Check on Conventional SVE Monitoring Systems

(from Marrin, 1988)

Redox Conditions	Process	Biogenic Gases
Oxidative	Aerobic Respiration [O_2]	CO_2
Slightly Reducing	Denitrification [NO_3^-]	N_2, CO_2
Reducing	Sulfate Reduction [SO_4^{2-}]	H_2S, CO_2
Highly Reducing	Methanogenesis [CO_2]	CH_4

Subsurface Redox Potentials

Aerated Soils:	+800 to +400 mv
Moderately Reduced Soils:	+400 to +100 mv
Reduced Soils:	+100 to -100 mv
Highly Reduced Soils:	-100 to -500 mv

(reprinted from Dragun, 1988)

Applications for In-Situ Bioremediation

"Micro" Scale Validation of "Macro" Scale Techniques

Estimation of Air Permeability & Water Vapor Concentration

Continuous Measurement of Gas-Phase Oxygen Concentrations

Analysis of Vapor-Phase Intermediates (halocarbons, H_2S, N_2O, H_2)

Calculation of Carbon Conversion Rates via CO_2 & CH_4 Production

Estimation of Gas->Aqueous Partitioning of Vapor Contaminants

Surface Geophysical Survey Methods

(modified after Hunt,1983)

Category	Applications	Limitations
Surface Seismic Refraction	Determine stratum depths and characteristic velocities, land or water.	May be unreliable unless velocities increase with depth and bedrock surface is irregular. Data are indirect and represent averages.
Surface Seismic Reflection	Not used on land for engineering studies. Useful offshore for continuous profiling.	Does not provide velocities. Computations of depths to stratum changes requires velocity data obtained by other means.
Electrical Resistivity	Locate saltwater boundaries, clean granular and clay strata; rock depth.	Difficult to interpret and subject to wide variations. Does not provide engineering properties.
Gravimeters	Detect major subsurface structures; faults, domes, intrusions, cavities.	Normally used only for cavity information for engineering studies.
Magnetometer	Mineral prospecting and location of large igneous masses.	Normally not used in engineering studies
Ground Penetrating Radar (GPR)	Provides subsurface profile; used to locate buried pipe, bedrock, boulders.	Shallow penetration. Normally used to identify buried drums and differences between fill and native soils.

Groundwater Treatment Technologies

(Those with data-after EPA RREL Treatability Database, 1991)

AAS	Activated Alumina Sorption
AFF	Aerobic Fixed Film
AL	Aerobic Lagoons
API	API Oil/Water Separator
AS	Activated Sludge
AirS	Air Stripping
AlkHyd	Alkaline Hydrolysis
AnFF	Anaerobic Fixed Film
AnL	Anaerobic Lagoons
BGAC	Biological Granular Activated Carbon
CAC	Chemically Assisted Clarification
ChOx	Chemical Oxidation (Parantheses shows oxidation chemical ie. ChOx(Cl) is chlorine, ChOx(Oz) is ozone, and ChOx(Sur) is surfactant)
ChPt	Chemical Precipitation
ChRed	Chemical Reduction
DAF	Dissolved Air Flotation
ED	Electrodialysis
Fil	Filtration
GAC	Activated Carbon (Granular)
IE	Ion Exchange
KPEG	Dechlorination of Toxics using an Alkoxide (Formed by the reactionof potassium hydroxide with polyethylene glycol (PEG400))
PACT	Powdered Activated Carbon Addition to Activated Sludge
RA	Resin Adsorption
RBC	Rotating Biological Contactor
RO	Reverse Osmosis
SBR	Sequential Batch Reactor
SCOx	Super Critical Oxidation
Sed	Sedimentation
SExt	Solvent Extraction
Soft	Water Softening
SS	Steam Stripping
TF	Trickling Filter
UF	Ultrafiltration
UV	Ultraviolet Radiation
WOx	Wet Air Oxidation

Soils Treatment Technology Matrix

Contaminant	Fluidized Bed Incineration	Rotary Kiln Incineration	Infrared Thermal Treatment	Pyrolysis-Incineration	Vitrification	Chemical Extraction	Chemical Treatment	Soil Washing/Soil Leaching	In-Situ Soil Flushing	Glycolate Dechlorination	Low Temperature Thermal Stripping	In-Situ Vacuum/Steam Extraction	Stabilization/Solidification	In-Situ Vitrification	Biodegradation	In-Situ Biodegradation
Organic																
Halogenated Volatiles	◒	●	●	◒	◒	◒	○	◒	◒	◒	◒	●	○	◒	◒	◒
Halogenated Semivolatiles	◒	●	●	◒	◒	◒	○	◒	◒	◒	◒	◒	◒	◒	◒	◒
Nonhalogenated Volatiles	◒	●	●	◒	◒	◒	○	◒	◒	○	◒	●	○	◒	◒	◒
Nonhalogenated Semivolatiles	◒	●	●	◒	◒	◒	○	◒	◒	○	◒	◒	◒	◒	●	◒
PCBs	◒	●	●	◒	◒	◒	○	◒	◒	◒	○	○	◒	◒	◒	◒
Pesticides	◒	●	◒	◒	◒	◒	○	◒	◒	◒	○	○	◒	◒	◒	◒
Organic Cyanides	◒	●	◒	◒	◒	◒	◒	◒	○	○	○	○	◒	◒	◒	◒
Organic Corrosives	◒	●	◒	◒	◒	◒	◒	◒	◒	○	○	○	◒	◒	X	X
Inorganic																
Volatile Metals	X	X	X	○	X	○	○	◒	◒	○	○	○	●	◒	○	X
Nonvolatile Metals	○	○	○	○	●	○	○	◒	◒	○	○	○	●	●	○	X
Asbestos	○	○	○	○	●	○	○	○	○	○	○	○	●	◒	○	○
Radioactive Materials	○	○	○	○	◒	○	○	◒	◒	○	○	○	●	●	○	X
Inorganic Corrosives	○	○	○	○	◒	○	◒	◒	◒	○	○	○	●	◒	○	X
Inorganic Cyanides	◒	◒	◒	◒	◒	○	◒	◒	○	○	○	○	●	◒	○	X
Reactive																
Oxidizers	◒	●	◒	◒	◒	X	●	◒	○	○	○	○	◒	◒	X	X
Reducers	◒	●	◒	◒	◒	X	●	◒	○	○	○	○	◒	◒	X	X

● *Demonstrated Effectiveness*
◒ *Potential Effectiveness*
○ *No Effectiveness*
X *Potential Adverse Impacts to Process or Environment*

SOIL TREATMENT TECHNOLOGIES MATRIX

TECHNOLOGY	Mobile Unit Status	Primary Waste Types Treated		Immobilization/ Removal/ Destruction Capability	Decrease in Waste Volume	Air Emissions or Residues Generated	Further Treatment/ Management Required	Relative Estimated Costs	
		Class	Form					Capital	O&M
THERMAL TREATMENT									
Incineration									
Fluidized Bed/Circulating Bed	Pilot	O	S,L	Very High	High	A,L,S	Inorganics in ash/landfill	High	High
Infrared	Pilot	O	S,L	Very High	High	A,L,S	Inorganics in ash/landfill	High	High
Low Temperature	Commercial	O	S	High	High	A,L,S	Inorganics in ash/landfill	High	High
Rotary Kiln	Commercial	O	S,L	Very High	High	A,L,S	Inorganics in ash/landfill	High	High
Pyrolysis									
Advanced Elec. Reactor	Pilot	O	S,L	Very High	High	A,L,S	Inorganics in ash/landfill	High	High
Plasma Arc	Pilot	O	L,S	Very High	High	A,L	Inorganics in ash/landfill	High	High
Vitrification	Pilot	O	S	Very High	High	A,S	Landfill	High	High
Wet Oxidation									
Supercritical Extraction	Pilot	O	L,GW,S	High	High	A,L,S	Inorganics in treated stream	High	High
IMMOBILIZATION									
Stabilization/Solidification									
Asphalt-based	Pilot	I	dry S	High	Increase	A	Landfill	Medium	Medium
Cement-based	Commercial	I	S	High	Increase	A	Landfill	Low	Low
Flyash or Lime-based	Commercial	I	S	High	Increase	A	Landfill	Low	Low
Surfactant-silicate	Pilot	O	S	High	Increase	A	Landfill	Low	Medium
REMOVAL TECHNOLOGIES									
Chemical									
Dechlorination	Commercial	O	L,S	High	High	L,S	Landfill	Medium	High
Extraction	Commercial	O	S	High	High	L,S	Landfill/destruction	Medium	High
Neutralization	Commercial	I,O	S,L,GW	High	Moderate	A,S	Dewatering/Landfill	Low	Medium
Oxidation-Reduction	Commercial	I,O	S,L,GW	Moderate	Moderate	A,S	Dewatering/Landfill	Low	Medium
Physical									
Air Stripping	Commercial	O	GW,S	High	High	A,L	Treatment of air emissions	Low	Low
Evaporation	Commercial	O,I	L,S	High	High	L,S	Landfill/destruction	Low	High
Filtration	Commercial	I	GW,L,S	High	High	L,S	Dewater/landfill	Low	Moderate
Phase Separation	Commercial	O,I	S,L	Moderate	Moderate	L,S	Landfill/destruction	Moderate	Low
Soil Washing	Pilot	O,I	S	Moderate	High	L,S	Washing Fluid Treatment	Moderate	Moderate
Vacuum/Steam Extraction	Commercial	O	S,L,GW	High	High	L	Recycle/destruction	Low	Low
Biological Treatment									
Aerobic	Commercial	O	GW,L,S	High	Moderate	L,S	Dewatering sludge/landfill/ destruction	Low	Low
Anaerobic	Commercial	O	GW,L,S	High	Moderate	L,S	Dewatering sludge/landfill	Low	Low

Mobile Unit Status
Commercial = Full Scale/Operational
Pilot = Demonstration Scale/Operational

Waste Class
O = Organic
I = Inorganic

Waste Form
S = Solids/Sludge
L = Concentrated Liquid
GW = Groundwater (low conc.)

Removal Efficiency
Very High - >99%
High - 95%
Moderate - 90%

Emissions or Residues Generated Byproduct
A = Air
L = Liquid, conc.
S = Solid

AEG Los Angeles Prog.

Exhibit 7.1-1

Soil Classification Chart

Unified Soil Classification System

MAJOR DIVISIONS			GRAPH SYMBOL	LETTER SYMBOL	TYPICAL DESCRIPTION
COARSE GRAINED SOILS More than 50% of Material is <u>Larger</u> than No. 200 Sieve Size.	GRAVEL AND GRAVELLY SOILS More than 50% of Coarse Fraction <u>Retained</u> on No. 4 Sieve.	CLEAN GRAVELS (Little or No Fines)		GW	Well-Graded Gravels, Gravel-Sand Mixtures, Little or No Fines.
				GP	Poorly-Graded Gravels, Gravel-Sand Mixtures, Little or No Fines
		GRAVELS WITH FINES (Appreciable Amount of Fines)		GM	Silty Gravels, Gravel-Sand-Silt Mixtures.
				GC	Clayey Gravels, Gravel-Sand-Clay Mixtures.
	SAND AND SANDY SOILS More than 50% of Coarse Fraction <u>Passing</u> No. 4 Sieve.	CLEAN SANDS (Little or No Fines)		SW	Well-Graded Sands, Gravelly Sands, Little or No Fines.
				SP	Poorly-Graded Sands, Gravelly Sands, Little or No Fines.
		SANDS WITH FINES (Appreciable Amount of Fines)		SM	Silty Sands, Sand-Silt Mixtures.
				SC	Clayey Sands, Sand-Clay Mixtures.
FINE GRAINED SOILS More than 50% of Material is <u>Smaller</u> than No. 200 Sieve Size.	SILT AND CLAYS (Liquid Limit <u>Less</u> than 50)			ML	Inorganic Silts and Very Fine Sands, Rock Flour, Silty or Clayey Fine Sands or Clayey Silts with Slight Plasticity.
				CL	Inorganic Clays of Low to Medium Plasticity, Gravelly Clays, Sandy Clays, Silty Clays, Lean Clays.
				OL	Organic Silts and Organic Silty Clays of Low Plasticity.
	SILT AND CLAYS (Liquid Limit <u>Greater</u> than 50)			MH	Inorganic Silts, Micaceous or Diatomaceous Fine Sand or Silty Soils.
				CH	Inorganic Clays of High Plasticity, Fat Clays.
				OH	Organic Clays of Meduim to High Plasticity, Organic Silts.
HIGHLY ORGANIC SOILS				PT	Peat, Humus, Swamp Soils with High Organic Contents.
ASH				ASH*	

Note: Dual Symbols Are Used to Indicate Borderline Soil Classifications

* Ash is not a standard USCS classification but is included for completeness

Exhibit 7.1-2
USCS Grain Size Categories

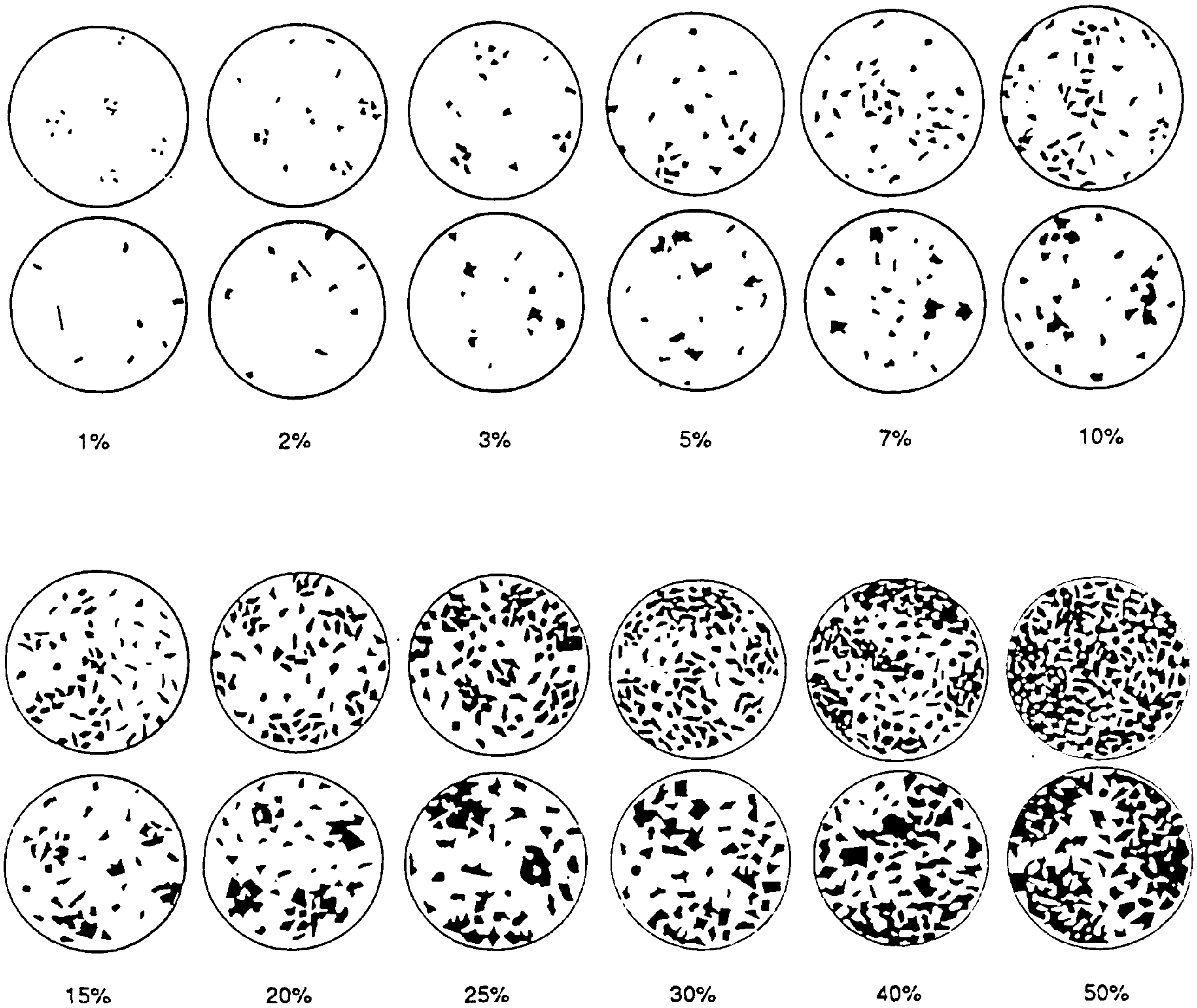
Description	Particle Diameter (mm)	U.S. Standard Sieve Size
Boulder	>300	>12 inches
Cobble	>75-300	3-12 inches
Coarse gravel	19 - 75	3/4 - 3 inches
Fine gravel	5 - 19	No. 4 - 3/4 inch
Coarse sand	2 - 5	Nos. 10 - 4
Medium sand	0.4 - 2	Nos. 40 - 10
Fine sand	0.08 - 0.4	Nos. 200 - 40
Silt	0.005 - 0.08	
Clay	<0.005	

Exhibit 7.1-3
Stratification Criteria

Laminated	less than 1/2 inch thick
Very Thinly Bedded	1/2 inch to 2 inches
Thinly Bedding	2 inches to 2 feet
Thickly Bedded	2 to 4 feet
Very Thickly Bedded	more than 4 feet

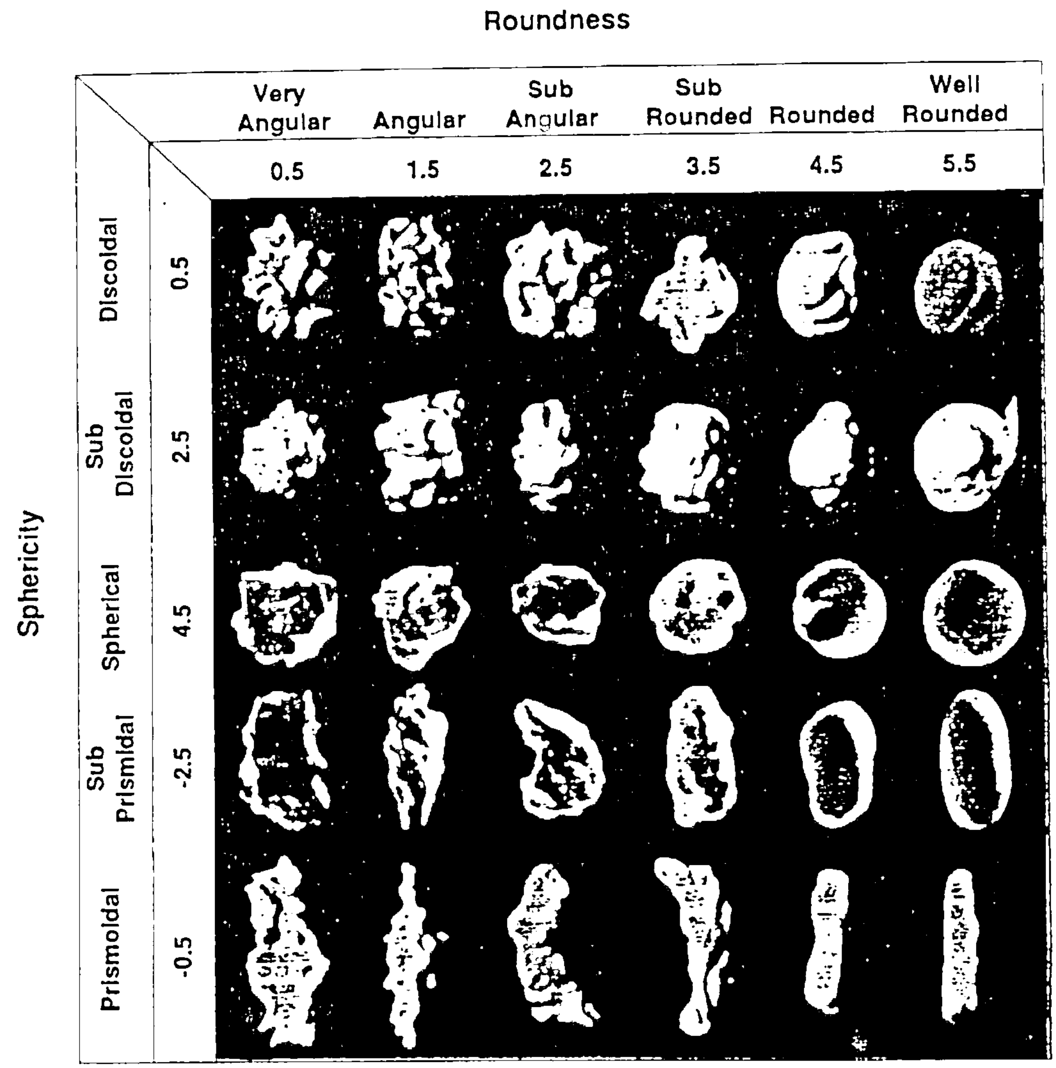
Exhibit 7-1.4

Comparison Chart for Estimating Percentage Composition



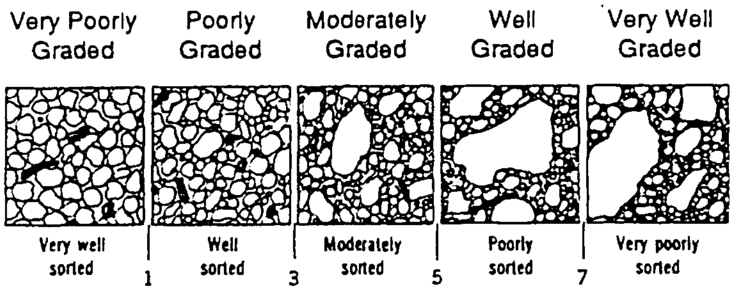
Reference: Compton, R.R. 1962. *Manual of Field Geology*. John Wiley & Sons, Inc. New York, N.Y. p. 332-333

Exhibit 7.1-5
Comparison Chart for Estimating Roundness and Sphericity



Reference: American Geologic Institute. 1982. "AGI Data Sheet 18.1": *in AGI Data Sheets*. Falls Church, Va.

Exhibit 7.1-6
Comparison Chart for Estimating Degree of Sorting



Terms for degrees of sorting. The numbers indicate the number of size-classes included by the great bulk (80 percent) of the material. The drawings represent sandstones as seen with a hand lens. Silt and clay-size materials are shown diagrammatically by the fine stipple.

Reference: Compton, R.R. 1962. *Manual of Geology.* John Wiley & Sons, Inc. New York, N.Y. p. 214.

Exhibit 7.1-7
USCS Field Sheet

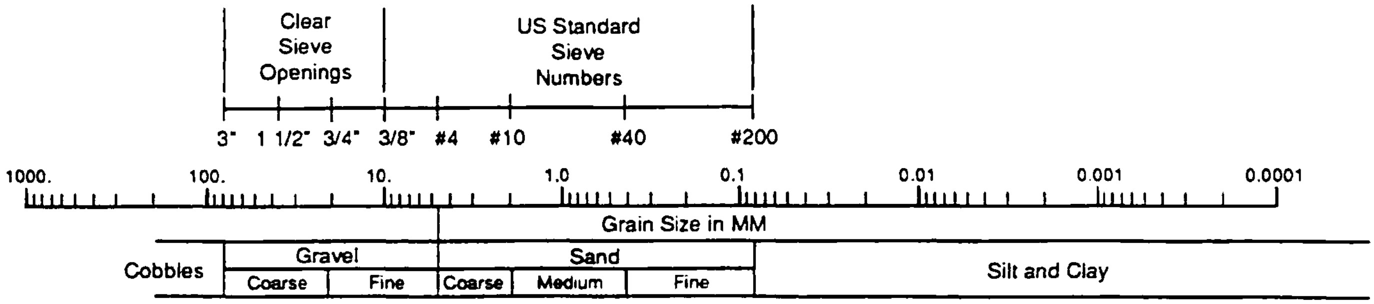
CONSISTENCY OF COHESIVE SOILS

CONSISTENCY	STANDARD PENETRATION RESIST[1]
Very Soft	0-2
Soft	2-4
Medium Stiff	4-8
Stiff	8-16
Very Stiff	16-32
Hard	More than 32

DENSITY OF GRANULAR SOILS

DENSITY	STANDARD PENETRATION RESISTANCE [1]
Very Loose	0-4
Loose	5-10
Medium Dense	11-30
Dense	31-50
Very Dense	Over 50

(1) Standard penetration resistence is the number of blows required to drive a 2 inch O.D. split barrel sampler 12 inches using a 140-pound hammer falling freely through 30 inches. The sampler is driven 18 inches and the number of blows recorded for each 6 inch interval. The summation of the final two intervals is the standard penetration resistance.



COARSE — GRAINED SOILS

Clean Gravels (Little or No Fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines
	GP	Poorly-graded gravels, gravel-sand mixtures, little or no fines
Gravels With Fines (Appreciable Amount of Fines)	GM	Silty gravels, gravel-sand-silt mixtures
	GC	Clayey gravels, gravel-sand-clay mixtures
Clean Sands (Little or No Fines)	SW	Well-graded sands, gravelly sands, little or no fines
	SP	Poorly-graded sands, gravelly sands, little or no fines
Sands With Fines (Appreciable Amount of Fines)	SM	Silty sands, sand-silt mixtures
	SC	Clayey sands, sand-clay mixtures

FINE — GRAINED/HIGHLY ORGANIC SOILS

Silts and Clays Liquid Limit (Less than 50)	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity
	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	OL	Organic silts and organic silty clays of low plasticity
Silts and Clays Liquid Limit (Greater that 50)	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils
	CH	Inorganic clays of high plasticity, fat clays
	OH	Organic clays of medium to high plasticity, organic silts
Highly Organic Soils	PT	Peat, humus, swamp soils with high organic contents

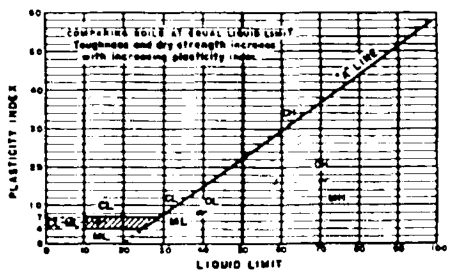
UNIFIED SOIL CLASSIFICATION
INCLUDING IDENTIFICATION AND DESCRIPTION

Major divisions			FIELD IDENTIFICATION PROCEDURES (Excluding particles larger than 3 inches and basing fractions on estimated weights)	GROUP SYMBOLS [a]	TYPICAL NAMES	INFORMATION REQUIRED FOR DESCRIBING SOILS	LABORATORY CLASSIFICATION CRITERIA	
COARSE GRAINED SOILS More than half of material is larger than No. 200 sieve size [b] (The No. 200 sieve size is about the smallest particle visible to the naked eye)	GRAVELS More than half of coarse fraction is larger than No. 4 sieve size (For visual classifications, the ¼" size may be used as equivalent to the No. 4 sieve size)	CLEAN GRAVELS (Little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes	GW	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name, indicate approximate percentages of sand and gravel, max size, angularity, surface condition, and hardness of the coarse grains, local or geologic name and other pertinent descriptive information, and symbol in parentheses	$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between one and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing	GP	Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting all gradation requirements for GW	
		GRAVELS WITH FINES (Appreciable amount of fines)	Non-plastic fines (for identification procedures see ML below)	GM	Silty gravels, poorly graded gravel-sand-silt mixtures	For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics	Atterberg limits below "A" line, or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols
			Plastic fines (for identification procedures see CL below)	GC	Clayey gravels, poorly graded gravel-sand-clay mixtures.		Atterberg limits above "A" line with PI greater than 7	
	SANDS More than half of coarse fraction is smaller than No. 4 sieve size	CLEAN SANDS (Little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	SW	Well graded sands, gravelly sands, little or no fines		$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between one and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing	SP	Poorly graded sands, gravelly sands, little or no fines	EXAMPLE:- Silty sand, gravelly, about 20% hard, angular gravel particles ½-in maximum size; rounded and subangular sand grains coarse to fine; about 15% non-plastic fines with low dry strength; well compacted and moist in place, alluvial sand; (SM)	Not meeting all gradation requirements for SW	
		SANDS WITH FINES (Appreciable amount of fines)	Non-plastic fines (for identification procedures see ML below)	SM	Silty sands, poorly graded sand-silt mixtures		Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			Plastic fines (for identification procedures see CL below)	SC	Clayey sands, poorly graded sand-clay mixtures		Atterberg limits above "A" line with PI greater than 7	

Use grain size curve in identifying the fractions as given under field identification

Determine percentages of gravel and sand from grain size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows:
Less than 5% GW, GP, SW, SP.
More than 12% GM, GC, SM, SC.
5% to 12% Borderline cases requiring use of dual symbols

Major divisions		IDENTIFICATION PROCEDURES ON FRACTION SMALLER THAN No. 40 SIEVE SIZE: DRY STRENGTH (CRUSHING CHARACTERISTICS)	DILATANCY (REACTION TO SHAKING)	TOUGHNESS (CONSISTENCY NEAR PLASTIC LIMIT)	GROUP SYMBOLS [a]	TYPICAL NAMES	INFORMATION REQUIRED FOR DESCRIBING SOILS
FINE GRAINED SOILS More than half of material is smaller than No. 200 sieve size.	SILTS AND CLAYS Liquid limit less than 50	None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name, indicate degree and character of plasticity, amount and maximum size of coarse grains; color in wet condition, odor if any, local or geologic name, and other pertinent descriptive information, and symbol in parentheses
		Medium to high	None to very slow	Medium	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	
		Slight to medium	Slow	Slight	OL	Organic silts and organic silt-clays of low plasticity.	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions
	SILTS AND CLAYS Liquid limit greater than 50	Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	
		High to very high	None	High	CH	Inorganic clays of high plasticity, fat clays	EXAMPLE:- Clayey silt, brown, slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess, (ML)
		Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity	
HIGHLY ORGANIC SOILS		Readily identified by color, odor, spongy feel and frequently by fibrous texture			Pt	Peat and other highly organic soils	



PLASTICITY CHART
FOR LABORATORY CLASSIFICATION OF FINE GRAINED SOILS

ADOPTED BY - CORPS OF ENGINEERS AND BUREAU OF RECLAMATION - JANUARY 1952

[a] Boundary classifications - Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well graded gravel-sand mixture with clay binder.
[b] All sieve sizes on this chart are US standard.

Unified soil classification chart. From drawing 103–D–347.

Designation: D 1452 - 80

An American National Sta[illegible]

Standard Practice for Soil Investigation and Sampling by Auger Borings[1]

This standard is issued under the fixed designation D 1452; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers equipment and procedures for the use of earth augers in shallow geotechnical exploration. This practice does not apply to sectional continuous flight augers.

2. Significance and Use

2.1 Auger borings often provide the simplest method of soil investigation and sampling. They may be used for any purpose where disturbed samples can be used and are valuable in connection with ground water level determination and indication of changes in strata and advancement of hole for spoon and tube sampling. Equipment required is simple and readily available. Depths of auger investigations are, however, limited by ground water conditions, soil characteristics, and the equipment used.

3. Apparatus

3.1 *Hand-Operated Augers*:

3.1.1 *Helical Augers*—Small lightweight augers generally available in sizes from 1 through 3 in. (25.4 through 76.2 mm).

3.1.1.1 *Spiral-Type Auger*, consisting of a flat thin metal strip, machine twisted to a spiral configuration of uniform pitch; having at one end, a sharpened or hardened point, with a means of attaching a shaft or extension at the opposite end.

3.1.1.2 *Ship-Type Auger*—Similar to a carpenter's wood bit. It is generally forged from steel and machined to the desired size and configuration. It is normally provided with sharpened and hardened nibs at the point end and with an integral shaft extending through its length for attachment of a handle or extension at the opposite end.

3.1.2 *Open Tubular Augers*, ranging in size from 1.5 through 8 in. (38.1 through 203.2 mm) and having the common characteristic of appearing essentially tubular when viewed from the digging end.

3.1.2.1 *Orchard-Barrel Type*, consisting essentially of a tube having cutting lips or nibs hardened and sharpened to penetrate the formation on one end and an adaptor fitting for an extension or handle on the opposite end.

3.1.2.2 *Open-Spiral Type*, consisting of a flat thin metal strip that has been helically wound around a circular mandrel to form a spiral in which the flat faces of the strip are parallel to the axis of the augered hole. The lower helix edges are hard-faced to improve wear characteristics. The opposite end is fitted with an adaptor for extension.

3.1.2.3 *Closed-Spiral Type*—Nearly identical to the ope[illegible] spiral type except, the pitch of the helically wound spira[illegible] much less than that of the open-spiral type.

3.1.3 *Post-Hole Augers*, generally 2 through 8 in. (5[illegible] through 203.2 mm), and having in common a means [illegible] blocking the escape of soil from the auger.

3.1.3.1 *Clam-Shell Type*, consisting of two halves, hing[illegible] to allow opening and closing for alternately digging [illegible] retrieving. It is not usable deeper than about 3.5 ft (1.07 [illegible]

3.1.3.2 *Iwan Type*, consisting of two tubular steel se[illegible]ments, connected at the top to a common member to form [illegible] nearly complete tube, but with diametrically opposed ope[illegible]ings. It is connected at the bottom by two radial blad[illegible] pitched to serve as cutters which also block the escape [illegible] contained soil. Attachment of handle or extension is at t[illegible] top connector.

3.2 *Machine-Operated Augers*:

3.2.1 *Helical Augers*, generally 8 through 48 in. (20[illegible] through 1219 mm), consisting essentially of a center sh[illegible] fitted with a shank or socket for application of power, a[illegible] having one to three complete 360° (6.28-rad) spirals [illegible] conveyance and storage of cut soil. Cutter bits and pilot b[illegible] are available in moderate and hard formation types a[illegible] normally replaceable in the field. They are normally ope[illegible]ated by heavy-duty, high-torque machines, designed [illegible] heavy construction work.

3.2.2 *Stinger Augers*, generally 6 through 30 in. (15[illegible] through 762 mm), are similar to the helical auger in 3.2[illegible] but lighter and generally smaller. They are commo[illegible] operated by light-duty machines for post and power p[illegible] holes.

3.2.3 *Disk Augers*, generally 10 through 30 in. (2[illegible] through 762 mm), consisting essentially of a flat, steel d[illegible] with diametrically opposed segments removed and having [illegible] shank or socket located centrally for application of powe[illegible] Replaceable cutter bits, located downward from the leadi[illegible] edges of the remaining disk, dig and load soil that is held [illegible] the disk by valves or shutters hinged at the disk in order [illegible] close the removed segments. The disk auger is specifica[illegible] designed to be operated by machines having limited verti[illegible] clearance between spindle and ground surface.

3.2.4 *Bucket Auger*, generally 12 through 48 in. (30[illegible] through 1219 mm), consisting essentially of a disk auge[illegible] without shank or socket, but hinge-mounted to the botto[illegible] of a steel tube or bucket of approximately the same diamete[illegible] as the disk auger. A socket or shank for power application [illegible] located in the top center of the bucket diametral cross pie[illegible] provided for the purpose.

3.3 *Casing* (when needed), consisting of pipe of slight[illegible] larger diameter than the auger used.

[1] This practice is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D 18.02 on Sampling and Related Field Testing for Soil Investigations.

Current edition approved June 12, 1980. Published August 1980. Originally published as D 1452 - 57 T. Last previous edition D 1452 - 65 (1972).

3.4 *Accessory Equipment*—Labels, field log sheets, sample sealing wax, sample bags, and other necessary tools and supplies.

4. Procedure

4.1 Make the auger boring by rotating and advancing the desired distance into the soil. Withdraw the auger from the hole and remove the soil for examination and test. Return the empty auger to the hole and repeat the procedure. Continue the sequence until the required depth is reached.

4.2 Casing is required in unstable soil in which the bore hole fails to stay open and especially when the boring is extended below the ground-water level. The inside diameter of the casing must be slightly larger than the diameter of the auger used. The casing shall be driven to a depth not greater than the top of the next sample and shall be cleaned out by means of the auger. The auger can then be inserted into the bore hole and turned below the bottom of the casing to obtain a sample.

4.3 The soil auger can be used both for boring the hole and for bringing up disturbed samples of the soil encountered. The structure of a cohesive soil is completely destroyed and the moisture may be changed by the auger. Seal all samples in a jar or other airtight container and label appropriately. If more than one type of soil is picked up in the sample, prepare a separate container for each type of soil.

4.4 *Field Observations*—Record complete ground water information in the field logs. Where casing is used, measure ground water levels, both before and after the casing is pulled. In sands, determine the water level at least 30 min after the boring is completed; in silts, at least 24 h. In clays, no accurate water level determination is possible unless pervious seams are present. As a precaution, however, water levels in clays shall be taken after at least 24 h.

5. Report

5.1 The data obtained in boring shall be recorded in the field logs and shall include the following:

5.1.1 Date of start and completion of boring,

5.1.2 Identifying number of boring,

5.1.3 Reference datum including direction and distance of boring relative to reference line of project or other suitable reference points,

5.1.4 Type and size of auger used in boring,

5.1.5 Depth of changes in strata,

5.1.6 Description of soil in each major stratum,

5.1.7 Ground water elevation and location of seepage zones, when found, and

5.1.8 Condition of augered hole upon removal of auger, that is, whether the hole remains open or the sides cave, when such can be observed.

Designation: D 1586 – 84

Standard Method for Penetration Test and Split-Barrel Sampling of Soils[1]

This standard is issued under the fixed designation D 1586; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This method has been approved for use by agencies of the Department of Defense and for listing in the DOD Index of Specifications and Standards.

1. Scope

1.1 This method describes the procedure, generally known as the Standard Penetration Test (SPT), for driving a split-barrel sampler to obtain a representative soil sample and a measure of the resistance of the soil to penetration of the sampler.

1.2 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For a specific precautionary statement, see 5.4.1.

1.3 The values stated in inch-pound units are to be regarded as the standard.

2. Referenced Documents

2.1 *ASTM Standards:*

D 2487 Test Method for Classification of Soils for Engineering Purposes[2]

D 2488 Practice for Description and Identification of Soils (Visual-Manual Procedure)[2]

D 4220 Practices for Preserving and Transporting Soil Samples[2]

3. Descriptions of Terms Specific to This Standard

3.1 *anvil*—that portion of the drive-weight assembly which the hammer strikes and through which the hammer energy passes into the drill rods.

3.2 *cathead*—the rotating drum or windlass in the rope-cathead lift system around which the operator wraps a rope to lift and drop the hammer by successively tightening and loosening the rope turns around the drum.

3.3 *drill rods*—rods used to transmit downward force and torque to the drill bit while drilling a borehole.

3.4 *drive-weight assembly*—a device consisting of the hammer, hammer fall guide, the anvil, and any hammer drop system.

3.5 *hammer*—that portion of the drive-weight assembly consisting of the 140 ± 2 lb (63.5 ± 1 kg) impact weight which is successively lifted and dropped to provide the energy that accomplishes the sampling and penetration.

3.6 *hammer drop system*—that portion of the drive-weight assembly by which the operator accomplishes the lifting and dropping of the hammer to produce the blow.

3.7 *hammer fall guide*—that part of the drive-weight assembly used to guide the fall of the hammer.

3.8 *N-value*—the blowcount representation of the penetration resistance of the soil. The *N*-value, reported in blows per foot, equals the sum of the number of blows required to drive the sampler over the depth interval of 6 to 18 in. (150 to 450 mm) (see 7.3).

3.9 ΔN—the number of blows obtained from each of the 6-in. (150-mm) intervals of sampler penetration (see 7.3).

3.10 *number of rope turns*—the total contact angle between the rope and the cathead at the beginning of the operator's rope slackening to drop the hammer, divided by 360° (see Fig. 1).

3.11 *sampling rods*—rods that connect the drive-weight assembly to the sampler. Drill rods are often used for this purpose.

3.12 *SPT*—abbreviation for Standard Penetration Test, a term by which engineers commonly refer to this method.

4. Significance and Use

4.1 This method provides a soil sample for identification purposes and for laboratory tests appropriate for soil obtained from a sampler that may produce large shear strain disturbance in the sample.

4.2 This method is used extensively in a great variety of geotechnical exploration projects. Many local correlations and widely published correlations which relate SPT blowcount, or *N*-value, and the engineering behavior of earthworks and foundations are available.

5. Apparatus

5.1 *Drilling Equipment*—Any drilling equipment that provides at the time of sampling a suitably clean open hole before insertion of the sampler and ensures that the penetration test is performed on undisturbed soil shall be acceptable. The following pieces of equipment have proven to be suitable for advancing a borehole in some subsurface conditions.

5.1.1 *Drag, Chopping, and Fishtail Bits*, less than 6.5 in. (162 mm) and greater than 2.2 in. (56 mm) in diameter may be used in conjuction with open-hole rotary drilling or casing-advancement drilling methods. To avoid disturbance of the underlying soil, bottom discharge bits are not permitted; only side discharge bits are permitted.

5.1.2 *Roller-Cone Bits*, less than 6.5 in. (162 mm) and greater than 2.2 in. (56 mm) in diameter may be used in

[1] This method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.02 on Sampling and Related Field Testing for Soil Investigations.

Current edition approved Sept. 11, 1984. Published November 1984. Originally published as D 1586 – 58 T. Last previous edition D 1586 – 67 (1974).

[2] *Annual Book of ASTM Standards*, Vol 04.08.

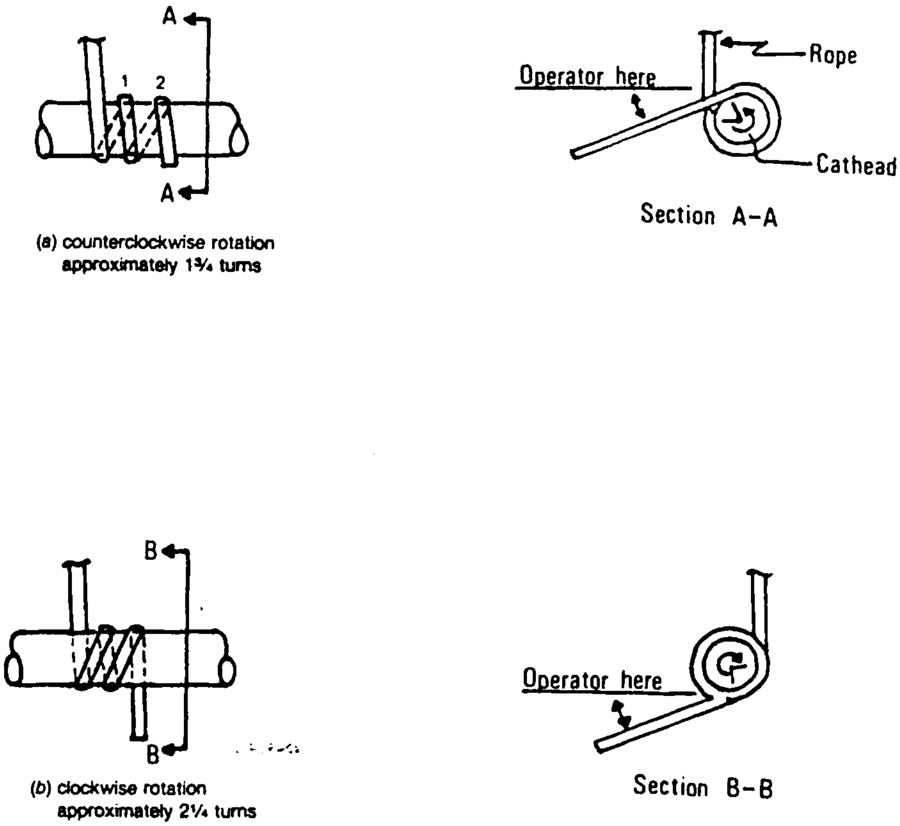


FIG. 1 Definitions of the Number of Rope Turns and the Angle for (a) Counterclockwise Rotation and (b) Clockwise Rotation of the Cathead

conjunction with open-hole rotary drilling or casing-advancement drilling methods if the drilling fluid discharge is deflected.

5.1.3 *Hollow-Stem Continuous Flight Augers*, with or without a center bit assembly, may be used to drill the boring. The inside diameter of the hollow-stem augers shall be less than 6.5 in. (162 mm) and greater than 2.2 in. (56 mm).

5.1.4 *Solid, Continuous Flight, Bucket and Hand Augers*, less than 6.5 in. (162 mm) and greater than 2.2 in. (56 mm) in diameter may be used if the soil on the side of the boring does not cave onto the sampler or sampling rods during sampling.

5.2 *Sampling Rods*—Flush-joint steel drill rods shall be used to connect the split-barrel sampler to the drive-weight assembly. The sampling rod shall have a stiffness (moment of inertia) equal to or greater than that of parallel wall "A" rod (a steel rod which has an outside diameter of 1⅝ in. (41.2 mm) and an inside diameter of 1⅛ in. (28.5 mm).

NOTE 1—Recent research and comparative testing indicates the type rod used, with stiffness ranging from "A" size rod to "N" size rod, will usually have a negligible effect on the *N*-values to depths of at least 100 ft (30 m).

5.3 *Split-Barrel Sampler*—The sampler shall be constructed with the dimensions indicated in Fig. 2. The driving shoe shall be of hardened steel and shall be replaced or repaired when it becomes dented or distorted. The use of liners to produce a constant inside diameter of 1⅜ in. (35 mm) is permitted, but shall be noted on the penetration record if used. The use of a sample retainer basket is permitted, and should also be noted on the penetration record if used.

NOTE 2—Both theory and available test data suggest that *N*-values may increase between 10 to 30 % when liners are used.

5.4 *Drive-Weight Assembly:*

5.4.1 *Hammer and Anvil*—The hammer shall weigh 140 ± 2 lb (63.5 ± 1 kg) and shall be a solid rigid metallic mass. The hammer shall strike the anvil and make steel on steel contact when it is dropped. A hammer fall guide permitting a free fall shall be used. Hammers used with the cathead and rope method shall have an unimpeded overlift capacity of at least 4 in. (100 mm). For safety reasons, the use of a hammer assembly with an internal anvil is encouraged.

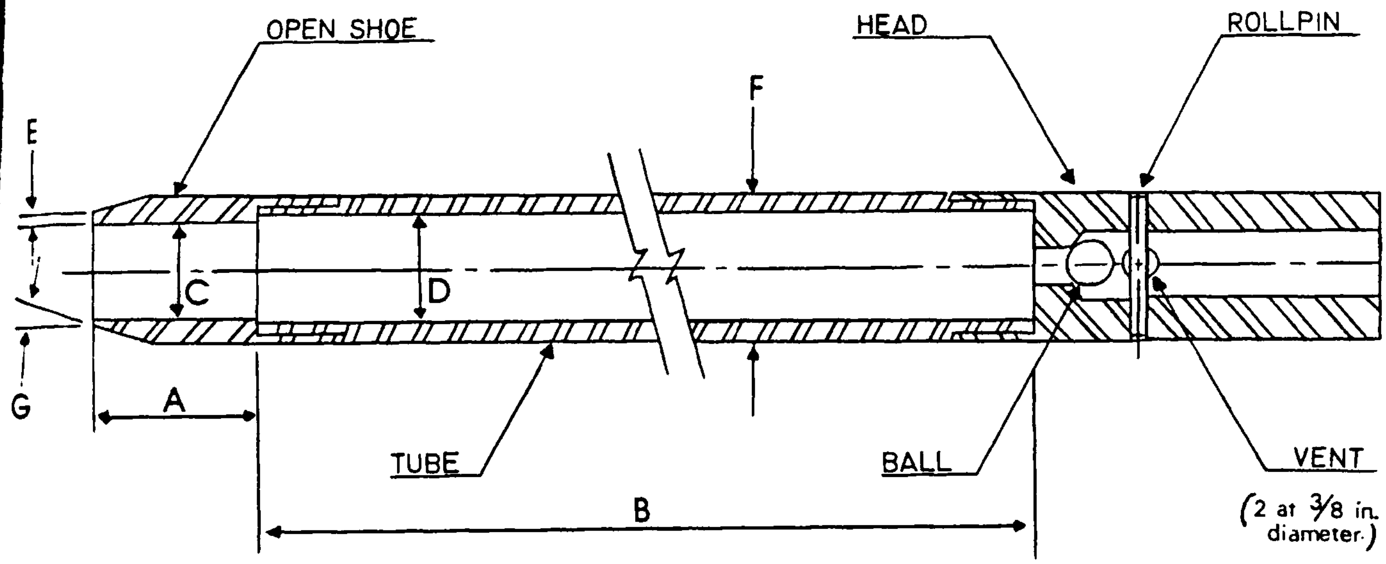
NOTE 3—It is suggested that the hammer fall guide be permanently marked to enable the operator or inspector to judge the hammer drop height.

5.4.2 *Hammer Drop System*—Rope-cathead, trip, semi-automatic, or automatic hammer drop systems may be used, providing the lifting apparatus will not cause penetration of the sampler while re-engaging and lifting the hammer.

5.5 *Accessory Equipment*—Accessories such as labels, sample containers, data sheets, and groundwater level measuring devices shall be provided in accordance with the requirements of the project and other ASTM standards.

6. Drilling Procedure

6.1 The boring shall be advanced incrementally to permit



A = 1.0 to 2.0 in. (25 to 50 mm)
B = 18.0 to 30.0 in. (0.457 to 0.762 m)
C = 1.375 ± 0.005 in. (34.93 ± 0.13 mm)
D = 1.50 ± 0.05 − 0.00 in. (38.1 ± 1.3 − 0.0 mm)
E = 0.10 ± 0.02 in. (2.54 ± 0.25 mm)
F = 2.00 ± 0.05 − 0.00 in. (50.8 ± 1.3 − 0.0 mm)
G = 16.0° to 23.0°

The 1½ in. (38 mm) inside diameter split barrel may be used with a 16-gage wall thickness split liner. The penetrating end of the drive shoe may be slightly rounded. Metal or plastic retainers may be used to retain soil samples.

FIG. 2 Split-Barrel Sampler

intermittent or continuous sampling. Test intervals and locations are normally stipulated by the project engineer or geologist. Typically, the intervals selected are 5 ft (1.5 mm) or less in homogeneous strata with test and sampling locations at every change of strata.

6.2 Any drilling procedure that provides a suitably clean and stable hole before insertion of the sampler and assures that the penetration test is performed on essentially undisturbed soil shall be acceptable. Each of the following procedures have proven to be acceptable for some subsurface conditions. The subsurface conditions anticipated should be considered when selecting the drilling method to be used.

6.2.1 Open-hole rotary drilling method.

6.2.2 Continuous flight hollow-stem auger method.

6.2.3 Wash boring method.

6.2.4 Continuous flight solid auger method.

6.3 Several drilling methods produce unacceptable borings. The process of jetting through an open tube sampler and then sampling when the desired depth is reached shall not be permitted. The continuous flight solid auger method shall not be used for advancing the boring below a water table or below the upper confining bed of a confined non-cohesive stratum that is under artesian pressure. Casing may not be advanced below the sampling elevation prior to sampling. Advancing a boring with bottom discharge bits is not permissible. It is not permissible to advance the boring for subsequent insertion of the sampler solely by means of previous sampling with the SPT sampler.

6.4 The drilling fluid level within the boring or hollow-stem augers shall be maintained at or above the in situ groundwater level at all times during drilling, removal of drill rods, and sampling.

7. Sampling and Testing Procedure

7.1 After the boring has been advanced to the desired sampling elevation and excessive cuttings have been removed, prepare for the test with the following sequence of operations.

7.1.1 Attach the split-barrel sampler to the sampling rods and lower into the borehole. Do not allow the sampler to drop onto the soil to be sampled.

7.1.2 Position the hammer above and attach the anvil to the top of the sampling rods. This may be done before the sampling rods and sampler are lowered into the borehole.

7.1.3 Rest the dead weight of the sampler, rods, anvil, and drive weight on the bottom of the boring and apply a seating blow. If excessive cuttings are encountered at the bottom of the boring, remove the sampler and sampling rods from the boring and remove the cuttings.

7.1.4 Mark the drill rods in three successive 6-in. (0.15-m) increments so that the advance of the sampler under the impact of the hammer can be easily observed for each 6-in. (0.15-m) increment.

7.2 Drive the sampler with blows from the 140-lb (63.5-kg) hammer and count the number of blows applied in each 6-in. (0.15-m) increment until one of the following occurs:

7.2.1 A total of 50 blows have been applied during any one of the three 6-in. (0.15-m) increments described in 7.1.4.

7.2.2 A total of 100 blows have been applied.

7.2.3 There is no observed advance of the sampler during the application of 10 successive blows of the hammer.

7.2.4 The sampler is advanced the complete 18 in. (0.45 m) without the limiting blow counts occurring as described in 7.2.1, 7.2.2, or 7.2.3.

7.3 Record the number of blows required to effect each 6 in. (0.15 m) of penetration or fraction thereof. The first 6 in. is considered to be a seating drive. The sum of the number of blows required for the second and third 6 in. of penetration is termed the "standard penetration resistance," or the "*N*-value." If the sampler is driven less than 18 in. (0.45 m), as permitted in 7.2.1, 7.2.2, or 7.2.3, the number of blows per each complete 6-in. (0.15-m) increment and per each partial increment shall be recorded on the boring log. For partial increments, the depth of penetration shall be reported to the nearest 1 in. (25 mm), in addition to the number of blows. If the sampler advances below the bottom of the boring under the static weight of the drill rods or the weight of the drill rods plus the static weight of the hammer, this information should be noted on the boring log.

7.4 The raising and dropping of the 140-lb (63.5-kg) hammer shall be accomplished using either of the following two methods:

7.4.1 By using a trip, automatic, or semi-automatic hammer drop system which lifts the 140-lb (63.5-kg) hammer and allows it to drop 30 ± 1.0 in. (0.76 m ± 25 mm) unimpeded.

7.4.2 By using a cathead to pull a rope attached to the hammer. When the cathead and rope method is used the system and operation shall conform to the following:

7.4.2.1 The cathead shall be essentially free of rust, oil, or grease and have a diameter in the range of 6 to 10 in. (150 to 250 mm).

7.4.2.2 The cathead should be operated at a minimum speed of rotation of 100 RPM, or the approximate speed of rotation shall be reported on the boring log.

7.4.2.3 No more than 2¼ rope turns on the cathead may be used during the performance of the penetration test, as shown in Fig. 1.

NOTE 4—The operator should generally use either 1¾ or 2¼ rope turns, depending upon whether or not the rope comes off the top (1¾ turns) or the bottom (2¼ turns) of the cathead. It is generally known and accepted that 2¾ or more rope turns considerably impedes the fall of the hammer and should not be used to perform the test. The cathead rope should be maintained in a relatively dry, clean, and unfrayed condition.

7.4.2.4 For each hammer blow, a 30-in. (0.76-m) lift and drop shall be employed by the operator. The operation of pulling and throwing the rope shall be performed rhythmically without holding the rope at the top of the stroke.

7.5 Bring the sampler to the surface and open. Record the percent recovery or the length of sample recovered. Describe the soil samples recovered as to composition, color, stratification, and condition, then place one or more representative portions of the sample into sealable moisture-proof containers (jars) without ramming or distorting any apparent stratification. Seal each container to prevent evaporation of soil moisture. Affix labels to the containers bearing job designation, boring number, sample depth, and the blow count per 6-in. (0.15-m) increment. Protect the samples against extreme temperature changes. If there is a soil change within the sampler, make a jar for each stratum and note its location in the sampler barrel.

8. Report

8.1 Drilling information shall be recorded in the field and shall include the following:

8.1.1 Name and location of job,

8.1.2 Names of crew,

8.1.3 Type and make of drilling machine,

8.1.4 Weather conditions,

8.1.5 Date and time of start and finish of boring,

8.1.6 Boring number and location (station and coordinates, if available and applicable),

8.1.7 Surface elevation, if available,

8.1.8 Method of advancing and cleaning the boring,

8.1.9 Method of keeping boring open,

8.1.10 Depth of water surface and drilling depth at the time of a noted loss of drilling fluid, and time and date when reading or notation was made,

8.1.11 Location of strata changes,

8.1.12 Size of casing, depth of cased portion of boring,

8.1.13 Equipment and method of driving sampler,

8.1.14 Type sampler and length and inside diameter of barrel (note use of liners),

8.1.15 Size, type, and section length of the sampling rods, and

8.1.16 Remarks.

8.2 Data obtained for each sample shall be recorded in the field and shall include the following:

8.2.1 Sample depth and, if utilized, the sample number,

8.2.2 Description of soil,

8.2.3 Strata changes within sample,

8.2.4 Sampler penetration and recovery lengths, and

8.2.5 Number of blows per 6-in. (0.15-m) or partial increment.

9. Precision and Bias

9.1 Variations in *N*-values of 100 % or more have been observed when using different standard penetration test apparatus and drillers for adjacent borings in the same soil formation. Current opinion, based on field experience, indicates that when using the same apparatus and driller, *N*-values in the same soil can be reproduced with a coefficient of variation of about 10 %.

9.2 The use of faulty equipment, such as an extremely massive or damaged anvil, a rusty cathead, a low speed cathead, an old, oily rope, or massive or poorly lubricated rope sheaves can significantly contribute to differences in *N*-values obtained between operator-drill rig systems.

9.3 The variability in *N*-values produced by different drill rigs and operators may be reduced by measuring that part of the hammer energy delivered into the drill rods from the sampler and adjusting *N* on the basis of comparative energies. A method for energy measurement and *N*-value adjustment is currently under development.

Designation: D 1587 – 83

Standard Practice for Thin-Walled Tube Sampling of Soils[1]

This standard is issued under the fixed designation D 1587; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This practice has been approved for use by agencies of the Department of Defense and for listing in the DOD Index of Specifications and Standards.

1. Scope

1.1 This practice covers a procedure for using a thin-walled metal tube to recover relatively undisturbed soil samples suitable for laboratory tests of structural properties. Thin-walled tubes used in piston, plug, or rotary-type samplers, such as the Denison or Pitcher, must comply with the portions of this practice which describe the thin-walled tubes (5.3).

NOTE 1—This practice does not apply to liners used within the above samplers.

2. Referenced Documents

2.1 *ASTM Standards:*

D 2488 Practice for Description and Identification of Soils (Visual-Manual Procedure)[2]

D 3550 Practice for Ring-Lined Barrel Sampling of Soils[2]

D 4220 Practices for Preserving and Transporting Soil Samples[2]

3. Summary of Practice

3.1 A relatively undisturbed sample is obtained by pressing a thin-walled metal tube into the in-situ soil, removing the soil-filled tube, and sealing the ends to prevent the soil from being disturbed or losing moisture.

4. Significance and Use

4.1 This practice, or Practice D 3550, is used when it is necessary to obtain a relatively undisturbed specimen suitable for laboratory tests of structural properties or other tests that might be influenced by soil disturbance.

5. Apparatus

5.1 *Drilling Equipment*—Any drilling equipment may be used that provides a reasonably clean hole; that does not disturb the soil to be sampled; and that does not hinder the penetration of the thin-walled sampler. Open borehole diameter and the inside diameter of driven casing or hollow stem auger shall not exceed 3.5 times the outside diameter of the thin-walled tube.

5.2 *Sampler Insertion Equipment*, shall be adequate to provide a relatively rapid continuous penetration force. For hard formations it may be necessary, although not recommended, to drive the thin-walled tube sampler.

5.3 *Thin-Walled Tubes*, should be manufactured as shown in Fig. 1. They should have an outside diameter of 2 to 5 in. and be made of metal having adequate strength for use in the soil and formation intended. Tubes shall be clean and free of all surface irregularities including projecting weld seams.

5.3.1 *Length of Tubes*—See Table 1 and 6.4.

5.3.2 *Tolerances*, shall be within the limits shown in Table 2.

5.3.3 *Inside Clearance Ratio*, should be 1 % or as specified by the engineer or geologist for the soil and formation to be sampled. Generally, the inside clearance ratio used should increase with the increase in plasticity of the soil being sampled. See Fig. 1 for definition of inside clearance ratio.

5.3.4 *Corrosion Protection*—Corrosion, whether from galvanic or chemical reaction, can damage or destroy both the thin-walled tube and the sample. Severity of damage is a function of time as well as interaction between the sample and the tube. Thin-walled tubes should have some form of protective coating. Tubes which will contain samples for more than 72 h shall be coated. The type of coating to be used may vary depending upon the material to be sampled. Coatings may include a light coat of lubricating oil, lacquer, epoxy, Teflon, and others. Type of coating must be specified by the engineer or geologist if storage will exceed 72 h. Plating of the tubes or alternate base metals may be specified by the engineer or geologist.

5.4 *Sampler Head*, serves to couple the thin-walled tube to the insertion equipment and, together with the thin-walled tube, comprises the thin-walled tube sampler. The sampler head shall contain a suitable check valve and a venting area to the outside equal to or greater than the area through the check valve. Attachment of the head to the tube shall be concentric and coaxial to assure uniform application of force to the tube by the sampler insertion equipment.

6. Procedure

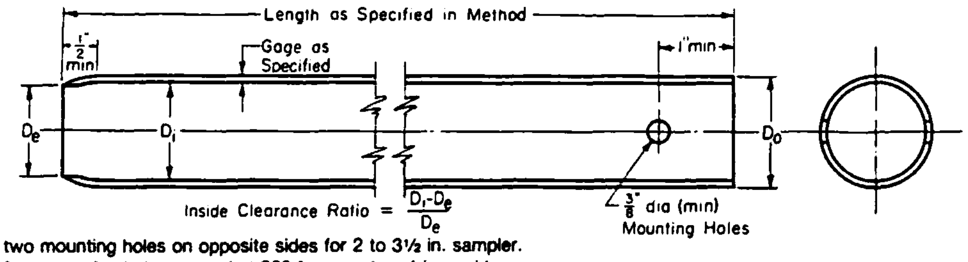
6.1 Clean out the borehole to sampling elevation using whatever method is preferred that will ensure the material to be sampled is not disturbed. If groundwater is encountered, maintain the liquid level in the borehole at or above groundwater level during the sampling operation.

6.2 Bottom discharge bits are not permitted. Side discharge bits may be used, with caution. Jetting through an open-tube sampler to clean out the borehole to sampling elevation is not permitted. Remove loose material from the center of a casing or hollow stem auger as carefully as

[1] This practice is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.02 on Sampling and Related Field Testing for Soil Investigations.

Current edition approved Aug. 17, 1983. Published October 1983. Originally published as D 1587 – 58 T. Last previous edition D 1587 – 74.

[2] *Annual Book of ASTM Standards*, Vol 04.08.



NOTE 1—Minimum of two mounting holes on opposite sides for 2 to 3½ in. sampler.

NOTE 2—Minimum of four mounting holes spaced at 90° for samplers 4 in. and larger.

NOTE 3—Tube held with hardened screws.

NOTE 4—Two-inch outside-diameter tubes are specified with an 18-gage wall thickness to comply with area ratio criteria accepted for "undisturbed samples." Users are advised that such tubing is difficult to locate and can be extremely expensive in small quantities. Sixteen-gage tubes are generally readily available.

Metric Equivalents

in.	mm
⅜	6.77
½	12.7
1	25.4
2	50.8
3½	88.9
4	101.6

FIG. 1 Thin-Walled Tube for Sampling

TABLE 1 Suitable Thin-Walled Steel Sample Tubes[A]

Outside diameter:			
in.	2	3	5
mm	50.8	76.2	127
Wall thickness:			
Bwg	18	16	11
in.	0.049	0.065	0.120
mm	1.24	1.65	3.05
Tube length:			
in.	36	36	54
m	0.91	0.91	1.45
Clearance ratio, %	1	1	1

[A] The three diameters recommended in Table 1 are indicated for purposes of standardization, and are not intended to indicate that sampling tubes of intermediate or larger diameters are not acceptable. Lengths of tubes shown are illustrative. Proper lengths to be determined as suited to field conditions.

TABLE 2 Dimensional Tolerances for Thin-Walled Tubes

Nominal Tube Diameters from Table 1[A] Tolerances, in.			
Size Outside Diameter	2	3	5
Outside diameter	+0.007	+0.010	+0.015
	−0.000	−0.000	−0.000
Inside diameter	+0.000	+0.000	+0.000
	−0.007	−0.010	−0.015
Wall thickness	±0.007	±0.010	±0.015
Ovality	0.015	0.020	0.030
Straightness	0.030/ft	0.030/ft	0.030/ft

[A] Intermediate or larger diameters should be proportional. Tolerances shown are essentially standard commercial manufacturing tolerances for seamless steel mechanical tubing. Specify only two of the first three tolerances; that is, O.D. and I.D., or O.D. and Wall, or I.D. and Wall.

possible to avoid disturbance of the material to be sampled.

NOTE 2—Roller bits are available in downward-jetting and diffused-jet configurations. Downward-jetting configuration rock bits are not acceptable. Diffuse-jet configurations are generally acceptable.

6.3 Place the sample tube so that its bottom rests on the bottom of the hole. Advance the sampler without rotation by a continuous relatively rapid motion.

6.4 Determine the length of advance by the resistance and condition of the formation, but the length shall never exceed 5 to 10 diameters of the tube in sands and 10 to 15 diameters of the tube in clays.

NOTE 3—Weight of sample, laboratory handling capabilities, transportation problems, and commercial availability of tubes will generally limit maximum practical lengths to those shown in Table 1.

6.5 When the formation is too hard for push-type insertion, the tube may be driven or Practice D 3550 may be used. Other methods, as directed by the engineer or geologist, may be used. If driving methods are used, the data regarding weight and fall of the hammer and penetration achieved must be shown in the report. Additionally, that tube must be prominently labeled a "driven sample."

6.6 In no case shall a length of advance be greater than the sample-tube length minus an allowance for the sampler head and a minimum of 3 in. for sludge-end cuttings.

NOTE 4—The tube may be rotated to shear bottom of the sample after pressing is complete.

6.7 Withdraw the sampler from the formation as carefully as possible in order to minimize disturbance of the sample.

7. Preparation for Shipment

7.1 Upon removal of the tube, measure the length of sample in the tube. Remove the disturbed material in the upper end of the tube and measure the length again. Seal the upper end of the tube. Remove at least 1 in. of material from the lower end of the tube. Use this material for soil description in accordance with Practice D 2488. Measure the overall sample length. Seal the lower end of the tube. Alternatively, after measurement, the tube may be sealed without removal of soil from the ends of the tube if so directed by the engineer or geologist.

NOTE 5—Field extrusion and packaging of extruded samples under the specific direction of a geotechnical engineer or geologist is permitted.

NOTE 6—Tubes sealed over the ends as opposed to those sealed with expanding packers should contain end padding in end voids in order to prevent drainage or movement of the sample within the tube.

7.2 Prepare and immediately affix labels or apply markings as necessary to identify the sample. Assure that the markings or labels are adequate to survive transportation and storage.

8. Report

8.1 The appropriate information is required as follows:

8.1.1 Name and location of the project,

8.1.2 Boring number and precise location on project,

8.1.3 Surface elevation or reference to a datum,

8.1.4 Date and time of boring—start and finish,

8.1.5 Depth to top of sample and number of sample,

8.1.6 Description of sampler: size, type of metal, type of coating,

8.1.7 Method of sampler insertion: push or drive,

8.1.8 Method of drilling, size of hole, casing, and drilling fluid used,

8.1.9 Depth to groundwater level: date and time measured,

8.1.10 Any possible current or tidal effect on water level,

8.1.11 Soil description in accordance with Practice D 2488,

8.1.12 Length of sampler advance, and

8.1.13 Recovery: length of sample obtained.

9. Precision and Bias

9.1 This practice does not produce numerical data; therefore, a precision and bias statement is not applicable.

Standard Test Method for Classification of Soils for Engineering Purposes[1]

This standard is issued under the fixed designation D 2487; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method has been approved for use by agencies of the Department of Defense and for listing in the DOD Index of Specifications and Standards.

1. Scope

1.1 This test method describes a system for classifying mineral and organo-mineral soils for engineering purposes based on laboratory determination of particle-size characteristics, liquid limit, and plasticity index and shall be used when precise classification is required.

NOTE 1—Use of this standard will result in a single classification group symbol and group name except when a soil contains 5 to 12 % fines or when the plot of the liquid limit and plasticity index values falls into the crosshatched area of the plasticity chart. In these two cases, a dual symbol is used, for example, GP-GM, CL-ML. When the laboratory test results indicate that the soil is close to another soil classification group, the borderline condition can be indicated with two symbols separated by a slash. The first symbol should be the one based on this standard. For example, CL/CH, GM/SM, SC/CL. Borderline symbols are particularly useful when the liquid limit value of clayey soils is close to 50. These soils can have expansive characteristics and the use of a borderline symbol (CL/CH, CH/CL) will alert the user of the assigned classifications of expansive potential.

1.2 The group symbol portion of this sytem is based on laboratory tests performed on the portion of a soil sample passing the 3-in. (75-mm) sieve (see Specification E 11).

1.3 As a classification system, this test method is limited to naturally occurring soils.

NOTE 2—The group names and symbols used in this test method may be used as a descriptive system applied to such materials as shale, claystone, shells, crushed rock, etc. See Appendix X2.

1.4 This test method is for qualitative application only.

NOTE 3—When quantitative information is required for detailed designs of important structures, this test method must be supplemented by laboratory tests or other quantitative data to determine performance characteristics under expected field conditions.

1.5 The system is based on the widely recognized Unified Soil Classification System which was adopted by several U.S. Government agencies in 1952 as an outgrowth of the Airfield Classification System developed by A. Casagrande.[2]

1.6 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 117 Test Method for Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing[3]

C 136 Method for Sieve Analysis of Fine and Coarse Aggregates[3]

C 702 Practice for Reducing Field Samples of Aggregate to Testing Size[3]

D 420 Practice for Investigating and Sampling Soil and Rock for Engineering Purposes[4]

D 421 Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants[4]

D 422 Method for Particle-Size Analysis of Soils[4]

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[4]

D 1140 Test Method for Amount of Material in Soils Finer than the No. 200 (75-μm) Sieve[4]

D 2216 Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures[4]

D 2217 Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants[4]

D 2488 Practice for Description and Identification of Soils (Visual-Manual Procedure)[4]

D 4318 Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils[4]

E 11 Specification for Wire-Cloth Sieves for Testing Purposes[3]

3. Summary of Test Method

3.1 As illustrated in Table 1, this classification system identifies three major soil divisions: coarse-grained soils, fine-grained soils, and highly organic soils. These three divisions are further subdivided into a total of 15 basic soil groups.

3.2 Based on the results of visual observations and prescribed laboratory tests, a soil is catalogued according to the basic soil groups, assigned a group symbol(s) and name, and

[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.07 on Identification and Classification of Soils.

Current edition approved Oct. 25, 1985. Published December 1985. Originally published as D 2487 - 66 T. Last previous edition D 2487 - 83.

[2] Casagrande, A., "Classification and Identification of Soils," *Transactions*, ASCE, 1948, p. 901.

[3] *Annual Book of ASTM Standards*, Vol 04.02.

[4] *Annual Book of ASTM Standards*, Vol 04.08.

TABLE 1 Soil Classification Chart

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests[A]				Soil Classification	
				Group Symbol	Group Name[B]
Coarse-Grained Soils More than 50 % retained on No. 200 sieve	Gravels More than 50 % of coarse fraction retained on No. 4 sieve	Clean Gravels Less than 5 % fines[C]	$Cu \geq 4$ and $1 \leq Cc \leq 3$[E]	GW	Well-graded gravel[F]
			$Cu < 4$ and/or $1 > Cc > 3$[E]	GP	Poorly graded gravel[F]
		Gravels with Fines More than 12 % fines[C]	Fines classify as ML or MH	GM	Silty gravel[F,G,H]
			Fines classify as CL or CH	GC	Clayey gravel[F,G,H]
	Sands 50 % or more of coarse fraction passes No. 4 sieve	Clean Sands Less than 5 % fines[D]	$Cu \geq 6$ and $1 \leq Cc \leq 3$[E]	SW	Well-graded sand[I]
			$Cu < 6$ and/or $1 > Cc > 3$[E]	SP	Poorly graded sand[I]
		Sands with Fines More than 12 % fines[D]	Fines classify as ML or MH	SM	Silty sand[G,H,I]
			Fines classify as CL or CH	SC	Clayey sand[G,H,I]
Fine-Grained Soils 50 % or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	inorganic	PI > 7 and plots on or above "A" line[J]	CL	Lean clay[K,L,M]
			PI < 4 or plots below "A" line[J]	ML	Silt[K,L,M]
		organic	$\frac{\text{Liquid limit - oven dried}}{\text{Liquid limit - not dried}} < 0.75$	OL	Organic clay[K,L,M,N] Organic silt[K,L,M,O]
	Silts and Clays Liquid limit 50 or more	inorganic	PI plots on or above "A" line	CH	Fat clay[K,L,M]
			PI plots below "A" line	MH	Elastic silt[K,L,M]
		organic	$\frac{\text{Liquid limit - oven dried}}{\text{Liquid limit - not dried}} < 0.75$	OH	Organic clay[K,L,M,P] Organic silt[K,L,M,Q]
Highly organic soils		Primarily organic matter, dark in color, and organic odor		PT	Peat

[A] Based on the material passing the 3-in. (75-mm) sieve.

[B] If field sample contained cobbles or boulders, or both, add "with cobbles or boulders, or both" to group name.

[C] Gravels with 5 to 12 % fines require dual symbols:
- GW-GM well-graded gravel with silt
- GW-GC well-graded gravel with clay
- GP-GM poorly graded gravel with silt
- GP-GC poorly graded gravel with clay

[D] Sands with 5 to 12 % fines require dual symbols:
- SW-SM well-graded sand with silt
- SW-SC well-graded sand with clay
- SP-SM poorly graded sand with silt
- SP-SC poorly graded sand with clay

[E] $Cu = D_{60}/D_{10}$ $\quad Cc = \frac{(D_{30})^2}{D_{10} \times D_{60}}$

[F] If soil contains ≥ 15 % sand, add "with sand" to group name.

[G] If fines classify as CL-ML, use dual symbol GC-GM, or SC-SM.

[H] If fines are organic, add "with organic fines" to group name.

[I] If soil contains ≥ 15 % gravel, add "with gravel" to group name.

[J] If Atterberg limits plot in hatched area, soil is a CL-ML, silty clay.

[K] If soil contains 15 to 29 % plus No. 200, add "with sand" or "with gravel," whichever is predominant.

[L] If soil contains ≥ 30 % plus No. 200, predominantly sand, add "sandy" to group name.

[M] If soil contains ≥ 30 % plus No. 200, predominantly gravel, add "gravelly" to group name.

[N] PI ≥ 4 and plots on or above "A" line.

[O] PI < 4 or plots below "A" line.

[P] PI plots on or above "A" line.

[Q] PI plots below "A" line.

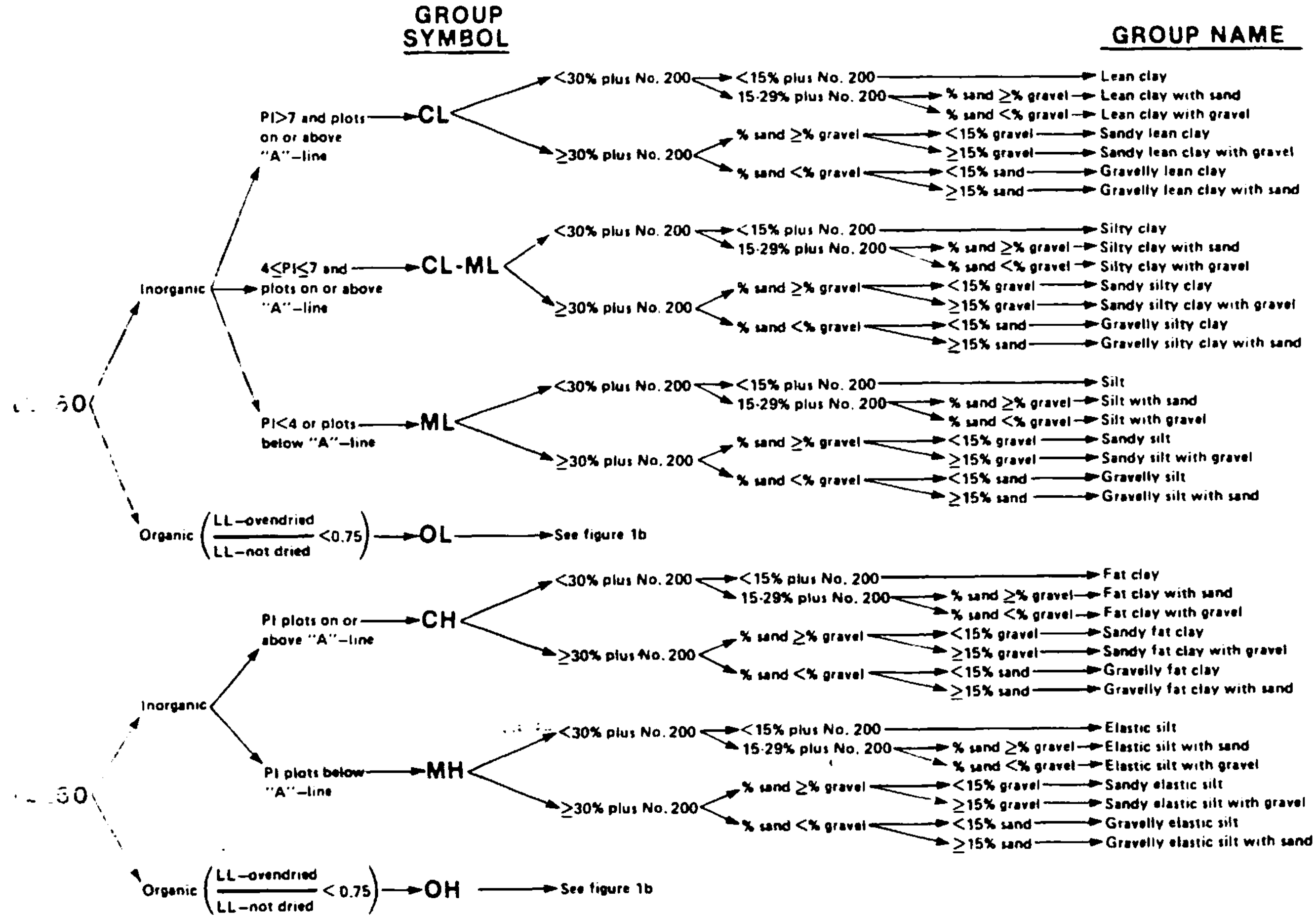


FIG. 1a Flow Chart for Classifying Fine-Grained Soil (50 % or More Passes No. 200 Sieve)

... classified. The flow charts, Fig. 1 for fine-grained soils and Fig. 2 for coarse-grained soils, can be used to assign the appropriate group symbol(s) and name.

4. Significance and Use

4.1 This test method classifies soils from any geographic location into categories representing the results of prescribed laboratory tests to determine the particle-size characteristics, the liquid limit, and the plasticity index.

4.2 The assigning of a group name and symbol(s) along with the descriptive information required in Practice D 2488 can be used to describe a soil to aid in the evaluation of its significant properties for engineering use.

4.3 The various groupings of this classification system have been devised to correlate in a general way with the engineering behavior of soils. This test method provides a useful first step in any field or laboratory investigation for geotechnical engineering purposes.

4.4 This test method may also be used as an aid in training personnel in the use of Practice D 2488.

5. Terminology

5.1 *Definitions*—Except as listed below, all definitions are in accordance with Terms and Symbols D 653.

NOTE 4—For particles retained on a 3-in. (75-mm) U.S. standard sieve, the following definitions are suggested:

Cobbles—particles of rock that will pass a 12-in. (300-mm) square opening and be retained on a 3-in. (75-mm) U.S. standard sieve, and

Boulders—particles of rock that will not pass a 12in. (300-mm) square opening

5.1.1 *gravel*—particles of rock that will pass a 3-in. (75-mm) sieve and be retained on a No. 4 (4.75-mm) U.S. standard sieve with the following subdivisions:

Coarse—passes 3-in. (75-mm) sieve and retained on ¾-in. (19-mm) sieve, and

Fine—passes ¾-in. (19-mm) sieve and retained on No. 4 (4.75-mm) sieve.

5.1.2 *sand*—particles of rock that will pass a No. 4 (4.75-mm) sieve and be retained on a No. 200 (75-μm) U.S. standard sieve with the following subdivisions:

Coarse—passes No. 4 (4.75-mm) sieve and retained on No. 10 (2.00-mm) sieve,

Medium—passes No. 10 (2.00-mm) sieve and retained on No. 40 (425-μm) sieve, and

Fine—passes No. 40 (425-μm) sieve and retained on No. 200 (75-μm) sieve.

5.1.3 *clay*—soil passing a No. 200 (75-μm) U.S. standard sieve that can be made to exhibit plasticity (putty-like properties) within a range of water contents and that exhibits considerable strength when air dry. For classification, a clay is a fine-grained soil, or the fine-grained portion of a soil, with a plasticity index equal to or greater than 4, and the plot

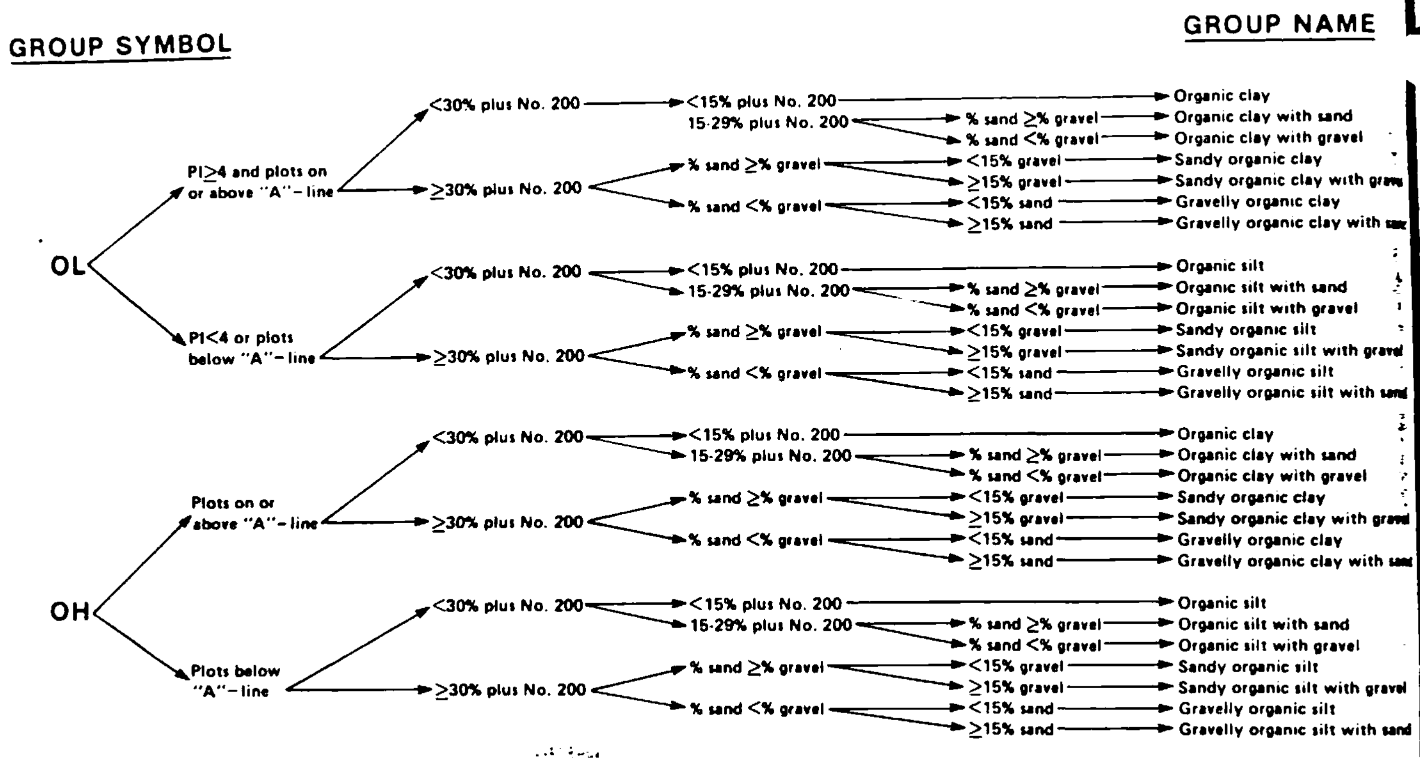


FIG. 1b Flow Chart for Classifying Organic Fine-Grained Soil (50 % or More Passes No. 200 Sieve)

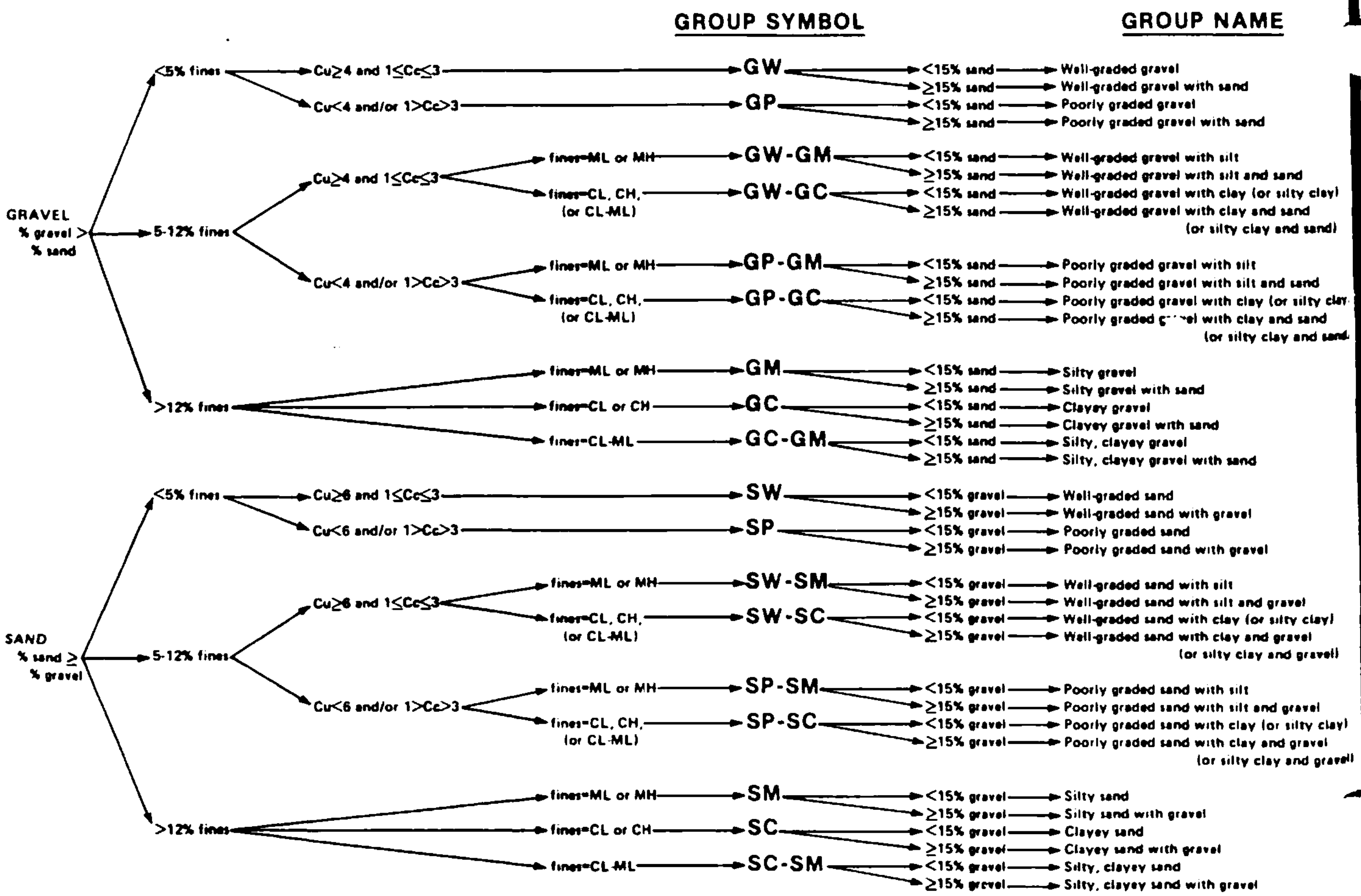


FIG. 2 Flow Chart for Classifying Coarse-Grained Soils (More Than 50 % Retained on No. 200 Sieve)

...plasticity index versus liquid limit falls on or above the "A" line.

5.1.4 *Silt*—soil passing a No. 200 (75-μm) U.S. standard sieve that is nonplastic or very slightly plastic and that exhibits little or no strength when air dry. For classification, a silt is a fine-grained soil, or the fine-grained portion of a soil, with a plasticity index less than 4 or if the plot of plasticity index versus liquid limit falls below the "A" line.

5.1.5 *Organic clay*—a clay with sufficient organic content to influence the soil properties. For classification, an organic clay is a soil that would be classified as a clay except that its liquid limit value after oven drying is less than 75 % of its liquid limit value before oven drying.

5.1.6 *Organic silt*—a silt with sufficient organic content to influence the soil properties. For classification, an organic silt is a soil that would be classified as a silt except that its liquid limit value after oven drying is less than 75 % of its liquid limit value before oven drying.

5.1.7 *Peat*—a soil composed of vegetable tissue in various stages of decomposition usually with an organic odor, a dark-brown to black color, a spongy consistency, and a texture ranging from fibrous to amorphous.

5.2 *Descriptions of Terms Specific to This Standard:*

5.2.1 *Coefficient of curvature*, Cc—the ratio $(D_{30})^2/(D_{10} \times D_{60})$, where D_{60}, D_{30}, and D_{10} are the particle diameters corresponding to 60, 30, and 10 % finer on the cumulative particle-size distribution curve, respectively.

5.2.2 *Coefficient of uniformity*, Cu—the ratio D_{60}/D_{10}, where D_{60} and D_{10} are the particle diameters corresponding to 60 and 10 % finer on the cumulative particle-size distribution curve, respectively.

6. Apparatus

6.1 In addition to the apparatus that may be required for obtaining and preparing the samples and conducting the prescribed laboratory tests, a plasticity chart, similar to Fig. 3, and a cumulative particle-size distribution curve, similar to Fig. 4, are required.

NOTE 5—The "U" line shown on Fig. 3 has been empirically determined to be the approximate "upper limit" for natural soils. It is a good check against erroneous data, and any test results that plot above or to the left of it should be verified.

7. Sampling

7.1 Samples shall be obtained and identified in accordance with a method or methods, recommended in Recommended Practice D 420 or by other accepted procedures.

7.2 For accurate identification, the minimum amount of test sample required for this test method will depend on which of the laboratory tests need to be performed. Where only the particle-size analysis of the sample is required, specimens having the following minimum dry weights are required:

Maximum Particle Size, Sieve Opening	Minimum Specimen Size, Dry Weight
4.75 mm (No. 4)	100 g (0.25 lb)
9.5 mm (3/8 in.)	200 g (0.5 lb)
19.0 mm (3/4 in.)	1.0 kg (2.2 lb)
38.1 mm (1 1/2 in.)	8.0 kg (18 lb)
75.0 mm (3 in.)	60.0 kg (132 lb)

Whenever possible, the field samples should have weights two to four times larger than shown.

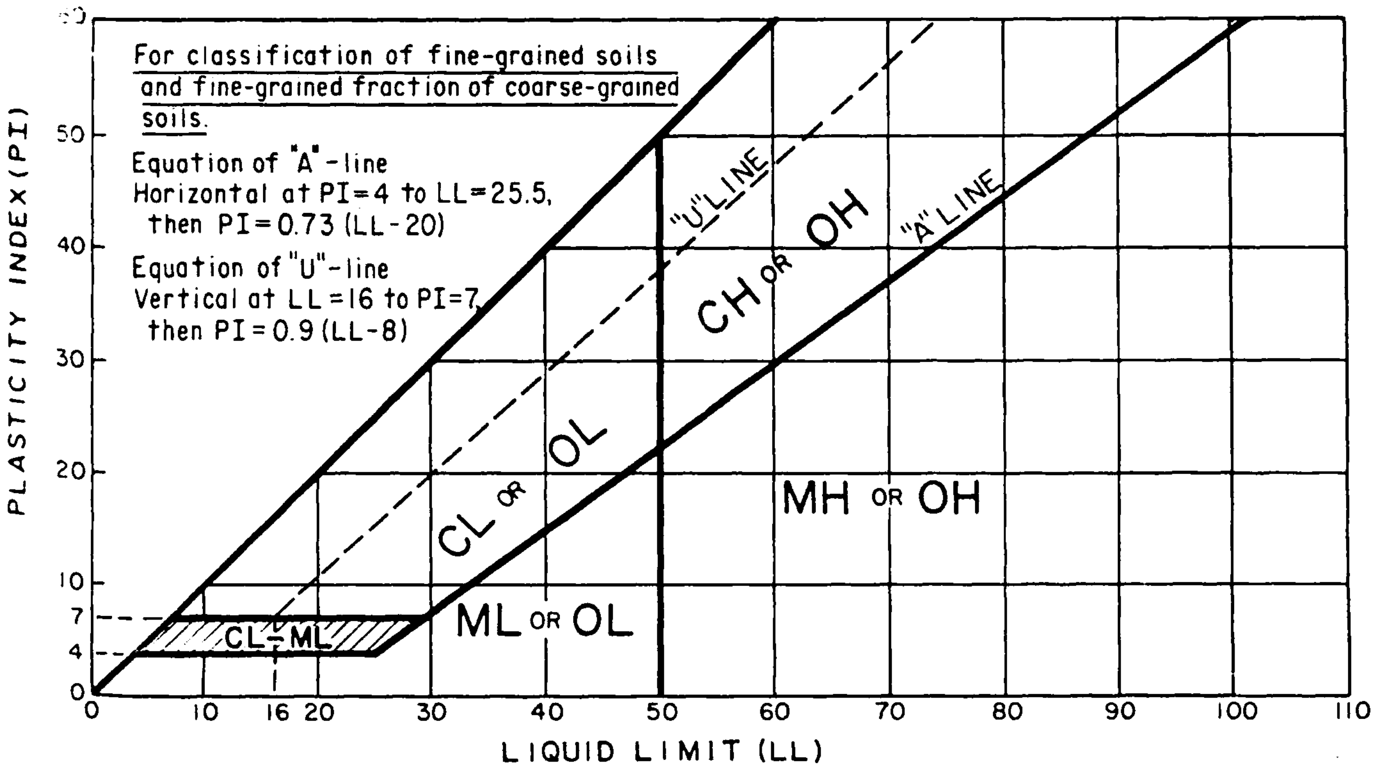
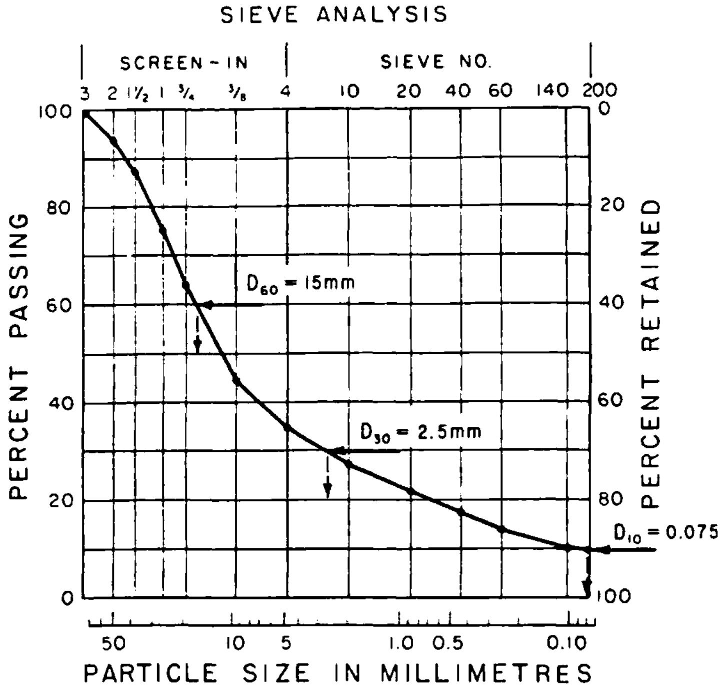


FIG. 3 Plasticity Chart



$$Cu = \frac{D_{60}}{D_{10}} = \frac{15}{0.075} = 200 \qquad Cc = \frac{(D_{30})^2}{D_{10} \times D_{60}} = \frac{(2.5)^2}{0.075 \times 15} = 5.6$$

FIG. 4 Cumulative Particle-Size Plot

7.3 When the liquid and plastic limit tests must also be performed, additional material will be required sufficient to provide 150 g to 200 g of soil finer than the No. 40 (425-µm) sieve.

7.4 If the field sample or test specimen is smaller than the minimum recommended amount, the report shall include an appropriate remark.

8. Classification of Peat

8.1 A sample composed primarily of vegetable tissue in various stages of decomposition and has a fibrous to amorphous texture, a dark-brown to black color, and an organic odor should be designated as a highly organic soil and shall be classified as peat, PT, and not subjected to the classification procedures described hereafter.

9. Preparation for Classification

9.1 Before a soil can be classified according to this test method, generally the particle-size distribution of the minus 3-in. (75-mm) material and the plasticity characteristics of the minus No. 40 (425-µm) sieve material must be determined. See 9.8 for the specific required tests.

9.2 The preparation of the soil specimen(s) and the testing for particle-size distribution and liquid limit and plasticity index shall be in accordance with accepted standard procedures. Two procedures for preparation of the soil specimens for testing for soil classification purposes are given in Appendixes X3 and X4. Appendix X3 describes the wet preparation method and is the preferred method for cohesive soils that have never dried out and for organic soils.

9.3 When reporting soil classifications determined by this test method, the preparation and test procedures used shall be reported or referenced.

9.4 Although the test procedure used in determining the particle-size distribution or other considerations may require a hydrometer analysis of the material, a hydrometer analysis is not necessary for soil classification.

9.5 The percentage (by dry weight) of any plus 3-in. (75-mm) material must be determined and reported as auxiliary information.

9.6 The maximum particle size shall be determined (measured or estimated) and reported as auxiliary information.

9.7 When the cumulative particle-size distribution is required, a set of sieves shall be used which include the following sizes (with the largest size commensurate with the maximum particle size) with other sieve sizes as needed or required to define the particle-size distribution:

3-in. (75-mm)
¾-in.(19.0-mm)
No. 4 (4.75-mm)
No. 10 (2.00-mm)
No. 40 (425-µm)
No. 200 (75-µm)

9.8 The tests required to be performed in preparation for classification are as follows:

9.8.1 For soils estimated to contain less than 5 % fines, a plot of the cumulative particle-size distribution curve of the fraction coarser than the No. 200 (75-µm) sieve is required. The cumulative particle-size distribution curve may be plotted on a graph similar to that shown in Fig. 4.

9.8.2 For soils estimated to contain 5 to 15 % fines, a cumulative particle-size distribution curve, as described in 9.1, is required, and the liquid limit and plasticity index are required.

9.8.2.1 If sufficient material is not available to determine the liquid limit and plasticity index, the fines should be estimated to be either silty or clayey using the procedures described in Practice D 2488 and so noted in the report.

9.8.3 For soils estimated to contain 15 % or more fines, a determination of the percent fines, percent sand, and percent gravel is required, and the liquid limit and plasticity index are required. For soils estimated to contain 90 % fines or more, the percent fines, percent sand, and percent gravel may be estimated using the procedures described in Practice D 2488 and so noted in the report.

10. Preliminary Classification Procedure

10.1 Class the soil as fine-grained if 50 % or more by dry weight of the test specimen passes the No. 200 (75-µm) sieve and follow Section 11.

10.2 Class the soil as coarse-grained if more than 50 % by dry weight of the test specimen is retained on the No. 200 (75-µm) sieve and follow Section 12.

11. Procedure for Classification of Fine-Grained Soils (50 % or more by dry weight passing the No. 200 (75-µm) sieve)

11.1 The soil is an inorganic clay if the position of the plasticity index versus liquid limit plot, Fig. 3, falls on or above the "A" line, the plasticity index is greater than 4, and the presence of organic matter does not influence the liquid limit as determined in 11.3.2.

11.1.1 Classify the soil as a *lean clay*, CL, if the liquid limit is less than 50. See area identified as CL on Fig. 3.

11.1.2 Classify the soil as a *fat clay*, CH, if the liquid limit is 50 or greater. See area identified as CH on Fig. 3.

NOTE 6—In cases where the liquid limit exceeds 110 or the plasticity index exceeds 60, the plasticity chart may be expanded by maintaining the same scale on both axes and extending the "A" line at the indicated slope.

11.1.3 Classify the soil as a *silty clay*, CL-ML, if the position of the plasticity index versus liquid limit plot falls on or above the "A" line and the plasticity index is in the range of 4 to 7. See area identified as CL-ML on Fig. 3.

11.2 The soil is an inorganic silt if the position of the plasticity index versus liquid limit plot, Fig. 3, falls below the "A" line or the plasticity index is less than 4, and presence of organic matter does not influence the liquid limit as determined in 11.3.2.

11.2.1 Classify the soil as a *silt*, ML, if the liquid limit is less than 50. See area identified as ML on Fig. 3.

11.2.2 Classify the soil as an *elastic silt*, MH, if the liquid limit is 50 or greater. See area identified as MH on Fig. 3.

11.3 The soil is an organic silt or clay if organic matter is present in sufficient amounts to influence the liquid limit as determined in 11.3.2.

11.3.1 If the soil has a dark color and an organic odor when moist and warm, a second liquid limit test shall be performed on a test specimen which has been oven dried at 110 ± 5°C to a constant weight, typically over night.

11.3.2 The soil is an organic silt or organic clay if the liquid limit after oven drying is less than 75 % of the liquid limit of the original specimen determined before oven drying (see Procedure B of Practice D 2217).

11.3.3 Classify the soil as an *organic silt* or *organic clay*, OL, if the liquid limit (not oven dried) is less than 50 %. Classify the soil as an *organic silt*, OL, if the plasticity index is less than 4, or the position of the plasticity index versus liquid limit plot falls below the "A" line. Classify the soil as an *organic clay*, OL, if the plasticity index is 4 or greater and the position of the plasticity index versus liquid limit plot falls on or above the "A" line. See area identified as OL (or CL-ML) on Fig. 3.

11.3.4 Classify the soil as an *organic clay* or *organic silt*, OH, if the liquid limit (not oven dried) is 50 or greater. Classify the soil as an *organic silt*, OH, if the position of the plasticity index versus liquid limit plot falls below the "A" line. Classify the soil as an *organic clay*, OH, if the position of the plasticity index versus liquid-limit plot falls on or above the "A" line. See area identified as OH on Fig. 3.

11.4 If less than 30 % but 15 % or more of the test specimen is retained on the No. 200 (75-µm) sieve, the words "with sand" or "with gravel" (whichever is predominant) shall be added to the group name. For example, lean clay with sand, CL; silt with gravel, ML. If the percent of sand is equal to the percent of gravel, use "with sand."

11.5 If 30 % or more of the test specimen is retained on the No. 200 (75-µm) sieve, the words "sandy" or "gravelly" shall be added to the group name. Add the word "sandy" if 30 % or more of the test specimen is retained on the No. 200 (75-µm) sieve and the coarse-grained portion is predominantly sand. Add the word "gravelly" if 30 % or more of the test specimen is retained on the No. 200 (75-µm) sieve and the coarse-grained portion is predominantly gravel. For example, sandy lean clay, CL; gravelly fat clay, CH; sandy silt, ML. If the percent of sand is equal to the percent of gravel, use "sandy."

12. Procedure for Classification of Coarse-Grained Soils (more than 50 % retained on the No. 200 (75-µm) sieve)

12.1 Class the soil as gravel if more than 50 % of the coarse fraction [plus No. 200 (75-µm) sieve] is retained on the No. 4 (4.75-mm) sieve.

12.2 Class the soil as sand if 50 % or more of the coarse fraction [plus No. 200 (75-µm) sieve] passes the No. 4 (4.75-mm) sieve.

12.3 If 12 % or less of the test specimen passes the No. 200 (75-µm) sieve, plot the cumulative particle-size distribution, Fig. 4, and compute the coefficient of uniformity, Cu, and coefficient of curvature, Cc, as given in Eqs 1 and 2.

$$Cu = D_{60}/D_{10} \quad (1)$$

$$Cc = (D_{30})^2/(D_{10} \times D_{60}) \quad (2)$$

where:

D_{10}, D_{30}, and D_{60} = the particle-size diameters corresponding to 10, 30, and 60 %, respectively, passing on the cumulative particle-size distribution curve, Fig. 4.

NOTE 7—It may be necessary to extrapolate the curve to obtain the D_{10} diameter.

12.3.1 If less than 5 % of the test specimen passes the No. 200 (75-µm) sieve, classify the soil as a *well-graded gravel*, GW, or *well-graded sand*, SW, if Cu is greater than 4.0 for gravel or greater than 6.0 for sand, and Cc is at least 1.0 but not more than 3.0.

12.3.2 If less than 5 % of the test specimen passes the No. 200 (75-µm) sieve, classify the soil as *poorly graded gravel*, GP, or *poorly graded sand*, SP, if either the Cu or the Cc criteria for well-graded soils are not satisfied.

12.4 If more than 12 % of the test specimen passes the No. 200 (75-µm) sieve, the soil shall be considered a coarse-grained soil with fines. The fines are determined to be either clayey or silty based on the plasticity index versus liquid limit plot on Fig. 3. (See 9.8.2.1 if insufficient material available for testing).

12.4.1 Classify the soil as a *clayey gravel*, GC, or *clayey sand*, SC, if the fines are clayey, that is, the position of the plasticity index versus liquid limit plot, Fig. 3, falls on or above the "A" line and the plasticity index is greater than 7.

12.4.2 Classify the soil as a *silty gravel*, GM, or *silty sand*, SM, if the fines are silty, that is, the position of the plasticity index versus liquid limit plot, Fig. 3, falls below the "A" line or the plasticity index is less than 4.

12.4.3 If the fines plot as a silty clay, CL-ML, classify the soil as a *silty, clayey gravel*, GC-GM, if it is a gravel or a *silty, clayey sand*, SC-SM, if it is a sand.

12.5 If 5 to 12 % of the test specimen passes the No. 200 (75-µm) sieve, give the soil a dual classification using two group symbols.

12.5.1 The first group symbol shall correspond to that for a gravel or sand having less than 5 % fines (GW, GP, SW, SP), and the second symbol shall correspond to a gravel or sand having more than 12 % fines (GC, GM, SC, SM).

12.5.2 The group name shall correspond to the first group symbol plus "with clay" or "with silt" to indicate the plasticity characteristics of the fines. For example, well-graded gravel with clay, GW-GC; poorly graded sand with silt, SP-SM (See 9.8.2.1 if insufficient material available for testing).

NOTE 8—If the fines plot as a *silty clay*, CL-ML, the second group symbol should be either GC or SC. For example, a poorly graded sand with 10 % fines, a liquid limit of 20, and a plasticity index of 6 would be classified as a poorly graded sand with silty clay, SP-SC.

12.6 If the specimen is predominantly sand or gravel but contains 15 % or more of the other coarse-grained constituent, the words "with gravel" or "with sand" shall be added to the group name. For example, poorly graded gravel with sand, clayey sand with gravel.

12.7 If the field sample contained any cobbles or boulders or both, the words "with cobbles," or "with cobbles and boulders" shall be added to the group name. For example, silty gravel with cobbles, GM.

13. Report

13.1 The report should include the group name, group symbol, and the results of the laboratory tests. The particle-size distribution shall be given in terms of percent of gravel, sand, and fines. The plot of the cumulative particle-size distribution curve shall be reported if used in classifying the soil. Report appropriate descriptive information according to the procedures in Practice D 2488. A local or commercial name or geologic interpretation for the material may be added at the end of the descriptive information if identified as such. The test procedures used shall be referenced.

NOTE 9—*Example: Clayey Gravel with Sand and Cobbles* (GC)—46 % fine to coarse, hard, subrounded gravel; 30 % fine to coarse, hard, subrounded sand; 24 % clayey fines, LL = 38, PI = 19; weak reaction with HCl; original field sample had 4 % hard, subrounded cobbles; maximum dimension 150 mm.

In-Place Conditions—firm, homogeneous, dry, brown,

Geologic Interpretation—alluvial fan.

NOTE 10—Other examples of soil descriptions are given in Appendix X1.

14. Precision and Bias

14.1 This test method provides qualitative data only; therefore, a precision and bias statement is nonapplicable.

APPENDIXES

(Nonmandatory Information)

X1. EXAMPLES OF DESCRIPTIONS USING SOIL CLASSIFICATION

X1.1 The following examples show how the information required in 13.1 can be reported. The appropriate descriptive information from Practice D 2488 is included for illustrative purposes. The additional descriptive terms that would accompany the soil classification should be based on the intended use of the classification and the individual circumstances.

X1.1.1 *Well-Graded Gravel with Sand (GW)*—73 % fine to coarse, hard, subangular gravel; 23 % fine to coarse, hard, subangular sand; 4 % fines; Cc = 2.7, Cu = 12.4.

X1.1.2 *Silty Sand with Gravel (SM)*—61 % predominantly fine sand; 23 % silty fines, LL = 33, PI = 6; 16 % fine, hard, subrounded gravel; no reaction with HCl; (field sample smaller than recommended). *In-Place Conditions*—Firm, stratified and contains lenses of silt 1 to 2 in. thick, moist, brown to gray; in-place density = 106 lb/ft^3 and in-place moisture = 9 %.

X1.1.3 *Organic Clay (OL)*—100 % fines, LL (not dried) = 32, LL (oven dried) = 21, PI (not dried) = 10; wet, dark brown, organic odor, weak reaction with HCl.

X1.1.4 *Silty Sand with Organic Fines (SM)*—74 % fine to coarse, hard, subangular reddish sand; 26 % organic and silty dark-brown fines, LL (not dried) = 37, LL (oven dried) = 26, PI (not dried) = 6, wet, weak reaction with HCl.

X1.1.5 *Poorly Graded Gravel with Silt, Sand, Cobbles and Boulders (GP-GM)*—78 % fine to coarse, hard, subrounded to subangular gravel; 16 % fine to coarse, hard, subrounded to subangular sand; 6 % silty (estimated) fines; moist, brown; no reaction with HCl; original field sample had 7 % hard, subrounded cobbles and 2 % hard, subrounded boulders with a maximum dimension of 18 in.

X2. USING SOIL CLASSIFICATION AS A DESCRIPTIVE SYSTEM FOR SHALE, CLAYSTONE, SHELLS, SLAG, CRUSHED ROCK, ETC.

X2.1 The group names and symbols used in this test method may be used as a descriptive system applied to materials that exist in situ as shale, claystone, sandstone, siltstone, mudstone, etc., but convert to soils after field or laboratory processing (crushing, slaking, etc.).

X2.2 Materials such as shells, crushed rock, slag, etc., should be identified as such. However, the procedures used in this method for describing the particle size and plasticity characteristics may be used in the description of the material. If desired, a classification in accordance with this test method may be assigned to aid in describing the material.

X2.3 If a classification is used, the group symbol(s) and group names should be placed in quotation marks or noted with some type of distinguishing symbol. See examples.

X2.4 Examples of how soil classifications could be incorporated into a description system for materials that are not naturally occurring soils are as follows:

X2.4.1 *Shale Chunks*—Retrieved as 2 to 4-in. pieces of shale from power auger hole, dry, brown, no reaction with HCl. After laboratory processing by slaking in water for 24 h, material classified as "Sandy Lean Clay (CL)"—61 % clayey fines, LL = 37, PI = 16; 33 % fine to medium sand; 6 % gravel-size pieces of shale.

X2.4.2 *Crushed Sandstone*—Product of commercial crushing operation: "Poorly Graded Sand with Silt (SP-SM)"—91 % fine to medium sand; 9 % silty (estimated) fines; dry, reddish-brown, strong reaction with HCl.

X2.4.3 *Broken Shells*—62 % gravel-size broken shells; 31 % sand and sand-size shell pieces; 7 % fines; would be classified as "Poorly Graded Gravel with Sand (GP)".

X2.4.4 *Crushed Rock*—Processed gravel and cobbles from Pit No. 7; "Poorly Graded Gravel (GP)"—89 % fine, hard, angular gravel-size particles; 11 % coarse, hard, angular sand-size particles, dry, tan; no reaction with HCl; Cc = 2.4, Cu = 0.9.

X3. PREPARATION AND TESTING FOR CLASSIFICATION PURPOSES BY THE WET METHOD

X3.1 This appendix describes the steps in preparing a soil sample for testing for purposes of soil classification using a wet-preparation procedure.

X3.2 Samples prepared in accordance with this procedure should contain as much of their natural water content as possible and every effort should be made during obtaining, preparing, and transportating the samples to maintain the natural moisture.

X3.3 The procedures to be followed in this test method assume that the field sample contains fines, sand, gravel, and plus 3-in. (75-mm) particles and the cumulative particle-size distribution plus the liquid limit and plasticity index values are required (see 9.8). Some of the following steps may be omitted when they are not applicable to the soil being tested.

X3.4 If the soil contains plus No. 200 (75-µm) particles that would degrade during dry sieving, use a test procedure for determining the particle-size characteristics that prevents this degradation.

X3.5 Since this classification system is limited to the portion of a sample passing the 3-in. (75-mm) sieve, the plus 3-in. (75-mm) material shall be removed prior to the determination of the particle-size characteristics and the liquid limit and plasticity index.

X3.6 The portion of the field sample finer than the 3-in. (75-mm) sieve shall be obtained as follows:

X3.6.1 Separate the field sample into two fractions on a 3-in. (75-mm) sieve, being careful to maintain the natural water content in the minus 3-in. (75-mm) fraction. Any particles adhering to the plus 3-in. (75-mm) particles shall be brushed or wiped off and placed in the fraction passing the 3-in. (75-mm) sieve.

X3.6.2 Determine the air-dry or oven-dry weight of the fraction retained on the 3-in. (75-mm) sieve. Determine the total (wet) weight of the fraction passing the 3-in. (75-mm) sieve.

X3.6.3 Thoroughly mix the fraction passing the 3-in. (75-mm) sieve. Determine the water content, in accordance with Method D 2216, of a representative specimen with a minimum dry weight as required in 7.2. Save the water-content specimen for determination of the particle-size analysis in accordance with X3.8.

X3.6.4 Compute the dry weight of the fraction passing the 3-in. (75-mm) sieve based on the water content and total (wet) weight. Compute the total dry weight of the sample and calculate the percentage of material retained on the 3-in. (75-mm) sieve.

X3.7 Determine the liquid limit and plasticity index as follows:

X3.7.1 If the soil disaggregates readily, mix on a clean, hard surface and select a representative sample by quartering in accordance with Methods C 702.

X3.7.1.1 If the soil contains coarse-grained particles coated with and bound together by tough clayey material, take extreme care in obtaining a representative portion of the No. 40 (425-µm) fraction. Typically, a larger portion than normal has to be selected, such as the minimum weights required in 7.2.

X3.7.1.2 To obtain a representative specimen of a basically cohesive soil, it may be advantageous to pass the soil through a ¾-in. (19-mm) sieve or other convenient size so the material can be more easily mixed and then quartered or split to obtain the representative specimen.

X3.7.2 Process the representative specimen in accordance with Procedure B of Practice D 2217.

X3.7.3 Perform the liquid-limit test in accordance with Test Method D 4318, except the soil shall not be air dried prior to the test.

X3.7.4 Perform the plastic-limit test in accordance with Test Method D 4318, except the soil shall not be air dried prior to the test, and calculate the plasticity index.

X3.8 Determine the particle-size distribution as follows:

X3.8.1 If the water content of the fraction passing the 3-in. (75-mm) sieve was required (X3.6.3), use the water-content specimen for determining the particle-size distribution. Otherwise, select a representative specimen in accordance with Methods C 702 with a minimum dry weight as required in 7.2.

X3.8.2 If the cumulative particle-size distribution including a hydrometer analysis is required, determine the particle-size distribution in accordance with Method D 422. See 9.7 for the set of required sieves.

X3.8.3 If the cumulative particle-size distribution without a hydrometer analysis is required, determine the particle-size distribution in accordance with Method C 136. See 9.7 for the set of required sieves. The specimen should be soaked until all clayey aggregations have softened and then washed in accordance with Test Method C 117 prior to performing the particle-size distribution.

X3.8.4 If the cumulative particle-size distribution is not required, determine the percent fines, percent sand, and percent gravel in the specimen in accordance with Test Method C 117, being sure to soak the specimen long enough to soften all clayey aggregations, followed by Method C 136 using a nest of sieves which shall include a No. 4 (4.75-mm) sieve and a No. 200 (75-µm) sieve.

X3.8.5 Calculate the percent fines, percent sand, and percent gravel in the minus 3-in. (75-mm) fraction for classification purposes.

X4. AIR-DRIED METHOD OF PREPARATION OF SOILS FOR TESTING FOR CLASSIFICATION PURPOSES

X4.1 This appendix describes the steps in preparing a soil sample for testing for purposes of soil classification when air-drying the soil before testing is specified or desired or when the natural moisture content is near that of an air-dried state.

X4.2 If the soil contains organic matter or mineral colloids that are irreversibly affected by air drying, the wet-preparation method as described in Appendix X3 should be used.

X4.3 Since this classification system is limited to the portion of a sample passing the 3-in. (75-mm) sieve, the plus 3-in. (75-mm) material shall be removed prior to the determination of the particle-size characteristics and the liquid limit and plasticity index.

X4.4 The portion of the field sample finer than the 3-in. (75-mm) sieve shall be obtained as follows:

X4.4.1 Air dry and weigh the field sample.

X4.4.2 Separate the field sample into two fractions on a 3-in. (75-mm) sieve.

X4.4.3 Weigh the two fractions and compute the percentage of the plus 3-in. (75-mm) material in the field sample.

X4.5 Determine the particle-size distribution and liquid limit and plasticity index as follows (see 9.8 for when these tests are required):

X4.5.1 Thoroughly mix the fraction passing the 3-in. (75-mm) sieve.

X4.5.2 If the cumulative particle-size distribution including a hydrometer analysis is required, determine the particle-size distribution in accordance with Method D 422. See 9.7 for the set of sieves that is required.

X4.5.3 If the cumulative particle-size distribution without a hydrometer analysis is required, determine the particle-size distribution in accordance with Test Method D 1140 followed by Method C 136. See 9.7 for the set of sieves that is required.

X4.5.4 If the cumulative particle-size distribution is not required, determine the percent fines, percent sand, and percent gravel in the specimen in accordance with Test Method D 1140 followed by Method C 136 using a nest of sieves which shall include a No. 4 (4.75-mm) sieve and a No. 200 (75-µm) sieve.

X4.5.5 If required, determine the liquid limit and the plasticity index of the test specimen in accordance with Test Method D 4318.

Designation: D 2488 – 84

Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)[1]

This standard is issued under the fixed designation D 2488; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers procedures for the description of soils for engineering purposes.

1.2 This practice also describes a procedure for identifying soils, at the option of the user, based on the classification system described in Test Method D 2487. The identification is based on visual examination and manual tests. It must be clearly stated in reporting an identification that it is based on visual-manual procedures.

1.2.1 When precise classification of soils for engineering purposes is required, the procedures prescribed in Test Method D 2487 shall be used.

1.2.2 In this practice, the identification portion assigning a group symbol and name is limited to soil particles smaller than 75 mm).

1.2.3 The identification portion of this practice is limited to naturally occurring soils.

NOTE 1—This practice may be used as a descriptive system applied to such materials as shale, claystone, shells, crushed rock, etc. (See Appendix X2.)

1.3 The descriptive information in this practice may be used with other soil classification systems or for materials other than naturally occurring soils.

1.4 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For specific precautionary statements see Section 8.

1.5 The values stated in inch-pound units are to be regarded as the standard.

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 1452 Practice for Soil Investigation and Sampling by Auger Borings[2]

D 1586 Method for Penetration Test and Split-Barrel Sampling of Soils[2]

D 1587 Practice for Thin-Walled Tube Sampling of Soils[2]

D 2113 Practice for Diamond Core Drilling for Site Investigation[2]

D 2487 Test Method for Classification of Soils for Engineering Purposes[2]

3. Definitions

3.1 Except as listed below, all definitions are in accordance with Terminology D 653.

NOTE 2—For particles retained on a 3-in. (75-mm) US standard sieve, the following definitions are suggested:

Cobbles—particles of rock that will pass a 12-in. (300-mm) square opening and be retained on a 3-in. (75-mm) sieve, and

Boulders—particles of rock that will not pass a 12-in. (300-mm) square opening.

3.1.1 *clay*—soil passing a No. 200 (75-μm) sieve that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and that exhibits considerable strength when air-dry. For classification, a clay is a fine-grained soil, or the fine-grained portion of a soil, with a plasticity index equal to or greater than 4, and the plot of plasticity index versus liquid limit falls on or above the "A" line (see Fig. 3 of Test Method D 2487).

3.1.2 *gravel*—particles of rock that will pass a 3-in. (75-mm) sieve and be retained on a No. 4 (4.75-mm) sieve with the following subdivisions:

coarse—passes a 3-in. (75-mm) sieve and is retained on a ¾-in. (19-mm) sieve.

fine—passes a ¾-in. (19-mm) sieve and is retained on a No. 4 (4.75-mm) sieve.

3.1.3 *organic clay*—a clay with sufficient organic content to influence the soil properties. For classification, an organic clay is a soil that would be classified as a clay, except that its liquid limit value after oven drying is less than 75 % of its liquid limit value before oven drying.

3.1.4 *organic silt*—a silt with sufficient organic content to influence the soil properties. For classification, an organic silt is a soil that would be classified as a silt except that its liquid limit value after oven drying is less than 75 % of its liquid limit value before oven drying.

3.1.5 *peat*—a soil composed primarily of vegetable tissue in various stages of decomposition usually with an organic odor, a dark brown to black color, a spongy consistency, and a texture ranging from fibrous to amorphous.

3.1.6 *sand*—particles of rock that will pass a No. 4 (4.75-mm) sieve and be retained on a No. 200 (75-μm) sieve with the following subdivisions:

coarse—passes a No. 4 (4.75-mm) sieve and is retained on a No. 10 (2.00-mm) sieve.

medium—passes a No. 10 (2.00-mm) sieve and is retained on a No. 40 (425-μm) sieve.

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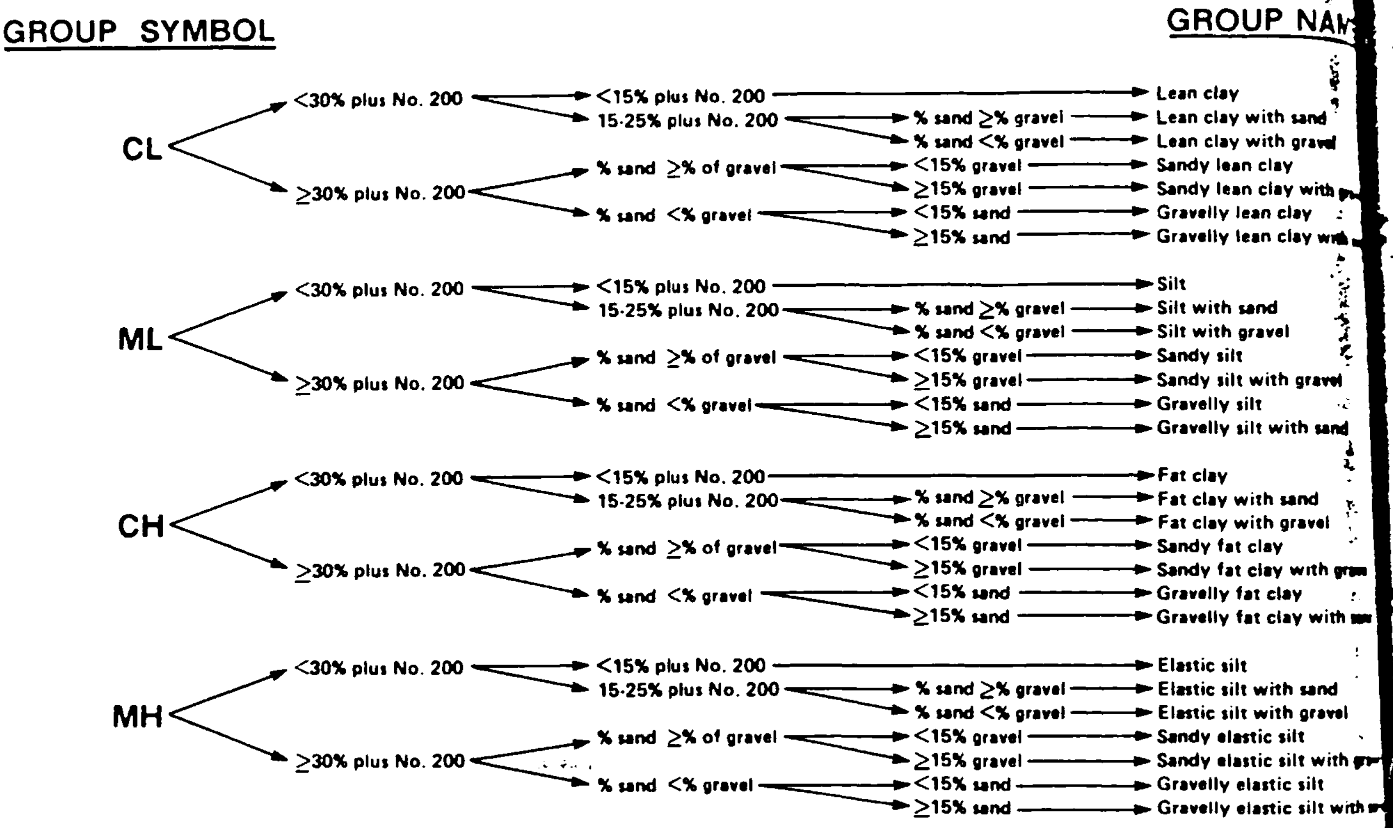
[1] This practice is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.07 on Identification and Classification of Soils.
Current edition approved Oct. 3, 1984. Published December 1984. Originally published as D 2488 – 66 T. Last previous edition D 2488 – 69 (1975).

[2] *Annual Book of ASTM Standards*, Vol 04.08.



NOTE—Percentages are based on estimating amounts of fines, sand, and gravel to the nearest 5 %.

FIG. 1a Flow Chart for Identifying Inorganic Fine-Grained Soil (50 % or more fines)

fine—passes a No. 40 (425-μm) sieve and is retained on a No. 200 (75-μm) sieve.

3.1.7 *silt*—soil passing a No. 200 (75-μm) sieve that is nonplastic or very slightly plastic and that exhibits little or no strength when air dry. For classification, a silt is a fine-grained soil, or the fine-grained portion of a soil, with a plasticity index less than 4, or the plot of plasticity index versus liquid limit falls below the "A" line (see Fig. 3 of Test Method D 2487).

4. Summary of Practice

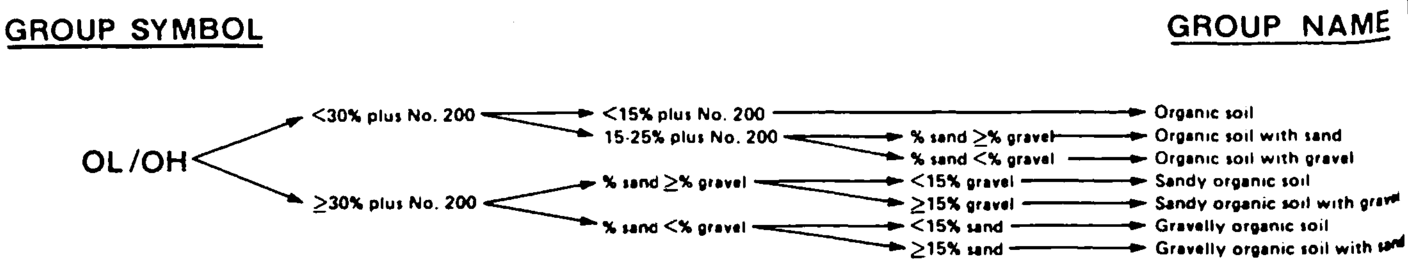
4.1 Using visual examination and simple manual tests, this practice gives standardized criteria and procedures for describing and identifying soils.

4.2 The soil can be given an identification by assigning a group symbol(s) and name. The flow charts, Figs. 1a and 1b for fine-grained soils, and Fig. 2, for coarse-grained soils, can be used to assign the appropriate group symbol(s) and nam If the soil has properties which do not distinctly place it in a specific group, borderline symbols may be used, s Appendix X3.

NOTE 3—It is suggested that a distinction be made between du *symbols* and *borderline symbols*.

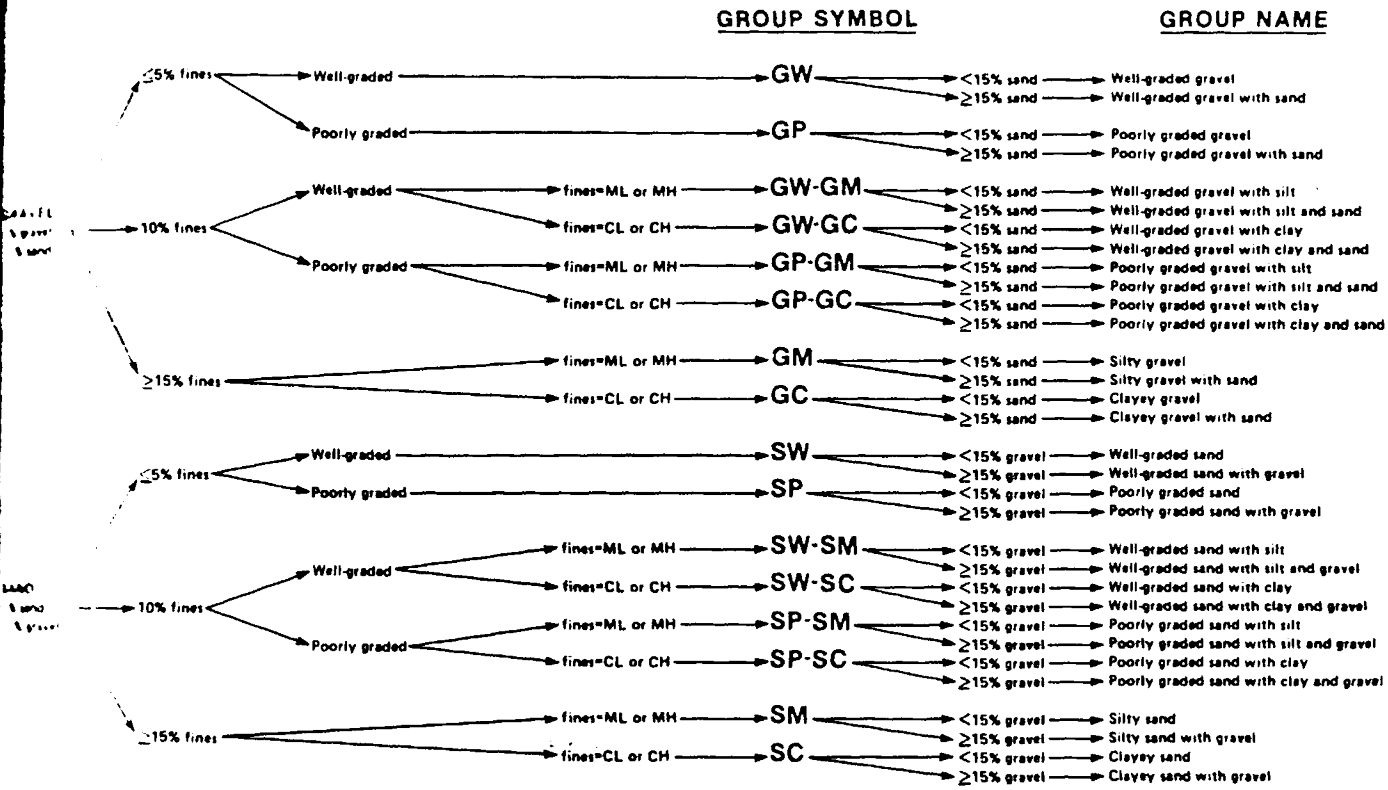
Dual Symbol—A dual symbol is two symbols separated by a hyphe for example, GP-GM, SW-SC, CL-ML used to indicate that the soil ha been identified as having the properties of a classification in accordan with Test Method D 2487 where two symbols are required. T symbols are required when the soil has between 5 and 12 % fines o when the liquid limit and plasticity index values plot in the CL-ML are of the plasticity chart.

Borderline Symbol—A borderline symbol is two symbols separat by a slash, for example, CL/CH, GM/SM, CL/ML. A borderline symb should be used to indicate that the soil has been identified as havin properties that do not distinctly place the soil into a specific group (se Appendix X3).



NOTE—Percentages are based on estimating amounts of fines, sand, and gravel to the nearest 5 %.

FIG. 1b Flow Chart for Identifying Organic Fine-Grained Soil (50 % or more fines)



Note—Percentages are based on estimating amounts of fines, sand, and gravel to the nearest 5 %.

FIG. 2 Flow Chart for Identifying Coarse-Grained Soils (less than 50 % fines)

5. Significance and Use

5.1 The descriptive information required in this practice can be used to describe a soil to aid in the evaluation of its significant properties for engineering use.

5.2 The descriptive information required in this practice should be used to supplement the classification of a soil as determined by Test Method D 2487.

5.3 This practice may be used in identifying soils using the classification group symbols and names as prescribed in Test Method D 2487. Since the names and symbols used in this practice to identify the soils are the same as those used in Test Method D 2487, it shall be clearly stated in reports and all other appropriate documents, that the classification symbol and name are based on visual-manual procedures.

5.4 This practice is to be used not only for identification of soils in the field, but also in the office, laboratory, or wherever soil samples are inspected and described.

5.5 This practice has particular value in grouping similar soil samples so that only a minimum number of laboratory tests need be run for positive soil classification.

Note 4—The ability to describe and identify soils correctly is learned more readily under the guidance of experienced personnel, but it may also be acquired systematically by comparing numerical laboratory test results for typical soils of each type with their visual and manual characteristics.

5.6 When describing and identifying soil samples from a given boring, test pit, or group of borings or pits, it is not necessary to follow all of the procedures in this practice for every sample. Soils which appear to be similar can be grouped together: one sample completely described and identified with the others referred to as similar based on performing only a few of the descriptive and identification procedures described in this practice.

6. Apparatus

6.1 *Required Apparatus:*

6.1.1 *Pocket Knife or Small Spatula.*

6.2 *Useful Auxiliary Apparatus:*

6.2.1 *Small Test Tube and Stopper* (or jar with a lid).

6.2.2 *Small Hand Lens.*

7. Reagents

7.1 *Purity of Water*—Unless otherwise indicated, references to water shall be understood to mean water from a city water supply or natural source, including non-potable water.

7.2 *Hydrochloric Acid*—A small bottle of dilute hydrochloric acid, HCl, one part HCl (10 *N*) to three parts water (This reagent is optional for use with this practice). See Section 8.

8. Safety Precautions

8.1 When preparing the dilute HCl solution of one part concentrated hydrochloric acid (10 *N*) to three parts of distilled water, slowly add acid into water following necessary safety precautions. Handle with caution and store safely. If solution comes into contact with the skin, rinse thoroughly with water.

8.2 Caution—Do not add water to acid.

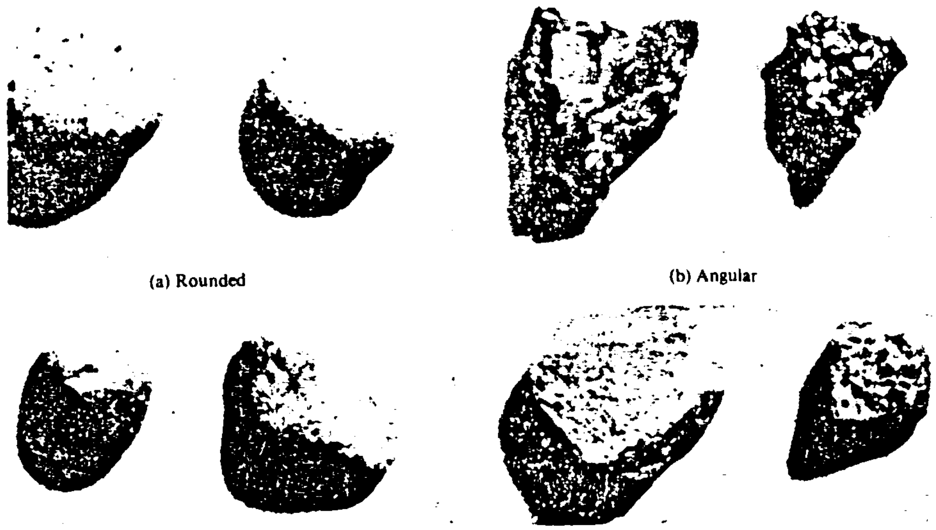


FIG. 3 Typical Angularity of Bulky Grains

9. Sampling

9.1 The sample shall be considered to be representative of the stratum from which it was obtained by an appropriate, accepted, or standard procedure.

NOTE 5—Preferably, the sampling procedure should be identified as having been conducted in accordance with Practices D 1452, D 1587, or D 2113, or Method D 1586.

9.2 The sample shall be carefully identified as to origin.

NOTE 6—Remarks as to the origin may take the form of a boring number and sample number in conjunction with a job number, a geologic stratum, a pedologic horizon or a location description with respect to a permanent monument, a grid system or a station number and offset with respect to a stated centerline and a depth or elevation.

9.3 For accurate description and identification, the minimum amount of the specimen to be examined shall be in accordance with the following schedule:

Maximum Particle Size, Sieve Opening	Minimum Specimen Size, Dry Weight
4.75 mm (No. 4)	100 g (0.25 lb)
9.5 mm (3/8 in.)	200 g (0.5 lb)
19.0 mm (3/4 in.)	1.0 kg (2.2 lb)
38.1 mm (1½ in.)	8.0 kg (18 lb)
75.0 mm (3 in.)	60.0 kg (132 lb)

NOTE 7—If random isolated particles are encountered that are significantly larger than the particles in the soil matrix, the soil matrix can be accurately described and identified in accordance with the preceeding schedule.

TABLE 1 Criteria for Describing Angularity of Coarse-Grained Particles (see Fig. 3)

Description	Criteria
Angular	Particles have sharp edges and relatively plane sides with unpolished surfaces
Subangular	Particles are similar to angular description but have rounded edges
Subrounded	Particles have nearly plane sides but have well-rounded corners and edges
Rounded	Particles have smoothly curved sides and no edges

9.4 If the field sample or specimen being examined smaller than the minimum recommended amount, t report shall include an appropriate remark.

10. Descriptive Information for Soils

10.1 *Angularity*—Describe the angularity of the sa (coarse sizes only), gravel, cobbles, and boulders, as angu subangular, subrounded, or rounded in accordance with criteria in Table 1 and Fig. 3. A range of angularity may stated, such as: subrounded to rounded.

10.2 *Shape*—Describe the shape of the gravel, cobbl and boulders as flat, elongated, or flat and elongated if t meet the criteria in Table 2 and Fig. 4. Otherwise, do t mention the shape. Indicate the fraction of the particles t have the shape, such as: one-third of the gravel particles flat.

10.3 *Color*—Describe the color. Color is an importa property in identifying organic soils, and within a giv locality it may also be useful in identifying materials similar geologic origin. If the sample contains layers patches of varying colors, this shall be noted and representative colors shall be described. The color shall described for moist samples. If the color represents a d condition, this shall be stated in the report.

10.4 *Odor*—Describe the odor if organic or unusual. So containing a significant amount of organic material usua have a distinctive odor of decaying vegetation. This especially apparent in fresh samples, but if the samples a dried, the odor may often be revived by heating a moisten

TABLE 2 Criteria for Describing Particle Shape (see Fig. 4)

The particle shape shall be described as follows where length, width, thickness refer to the greatest, intermediate, and least dimensions of a par respectively.

Flat	Particles with width/thickness > 3
Elongated	Particles with length/width > 3
Flat and elongated	Particles meet criteria for both flat and elongate

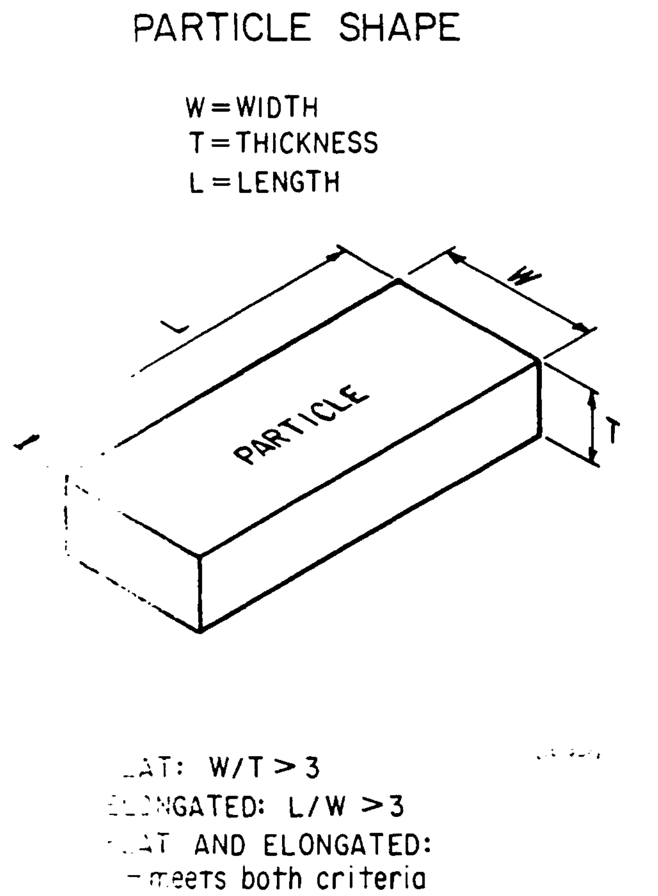


FIG. 4 Criteria for Particle Shape

TABLE 3 Criteria for Describing Moisture Condition

[illegible]	Criteria
[illegible]	Absence of moisture, dusty, dry to the touch
[illegible]	Damp but no visible water
[illegible]	Visible free water, usually soil is below water table

[illegible] If the odor is unusual (petroleum product, chemical, [illegible] the like), it shall be described.

[illegible] Moisture Condition—Describe the moisture condition as dr[illegible], moist, or wet, in accordance with the criteria in Table [illegible]

[illegible] HCl Reaction—Describe the reaction with HCl as [illegible] weak, or strong, in accordance with the critera in Table 4. Since calcium carbonate is a common cementing [illegible] a report of its presence on the basis of the reaction [illegible] hydrochloric acid is important.

[illegible] Consistency—For intact fine-grained soil, describe [illegible] as very soft, soft, firm, hard, or very hard, in [illegible] with the criteria in Table 5. This observation is [illegible] for soils with significant amounts of gravel.

TABLE 4 Criteria for Describing the Reaction With HCl

[illegible]	Criteria
[illegible]	No visible reaction
[illegible]	Some reaction, with bubbles forming slowly
[illegible]	Violent reaction, with bubbles forming immediately

TABLE 5 Criteria for Describing Consistency

Description	Criteria
Very soft	Thumb will penetrate soil more than 1 in. (25 mm)
Soft	Thumb will penetrate soil about 1 in. (25 mm)
Firm	Thumb will indent soil about ¼ in. (6 mm)
Hard	Thumb will not indent soil but readily indented with thumbnail
Very hard	Thumbnail will not indent soil

10.8 *Cementation*—Describe the cementation of intact coarse-grained soils as weak, moderate, or strong, in accordance with the criteria in Table 6.

10.9 *Structure*—Describe the structure of intact soils in accordance with the criteria in Table 7.

10.10 *Range of Particle Sizes*—For gravel and sand components, describe the range of particle sizes within each component as defined in 3.1.2 and 3.1.6. For example, about 20 % fine to coarse gravel, about 40 % fine to coarse sand.

10.11 *Maximum Particle Size*—Describe the maximum particle size found in the sample in accordance with the following information:

10.11.1 *Sand Size*—If the maximum particle size is a sand size, describe as fine, medium, or coarse as defined in 3.1.7. For example: maximum particle size, medium sand.

10.11.2 *Gravel Size*—If the maximum particle size is a gravel size, describe the maximum particle size as the smallest sieve opening that the particle will pass. For example, maximum particle size, 1½ in. (will pass a 1½-in. square opening but not a ¾-in. square opening).

10.11.3 *Cobble or Boulder Size*—If the maximum particle size is a cobble or boulder size, describe the maximum dimension of the largest particle. For example: maximum dimension, 18 in. (450 mm).

10.12 *Hardness*—Describe the hardness of coarse sand and larger particles as hard, or state what happens when the particles are hit by a hammer, for example, gravel-size particles fracture with considerable hammer blow, some gravel-size particles crumble with hammer blow. "Hard" means particles do not crack, fracture, or crumble under a hammer blow.

10.13 Additional comments shall be noted, such as the presence of roots or root holes, difficulty in drilling or augering hole, caving of trench or hole, or the presence of mica.

10.14 A local or commercial name or a geologic interpretation of the soil, or both, may be added if identified as such.

10.15 A classification or identification of the soil in accordance with other classification systems may be added if identified as such.

11. Identification of Peat

11.1 A sample composed primarily of vegetable tissue in various stages of decomposition that has a fibrous to amorphous texture, usually a dark brown to black color, and an organic odor, shall be designated as a highly organic soil and shall be identified as peat, PT, and not subjected to the

TABLE 6 Criteria for Describing Cementation

Description	Criteria
Weak	Crumbles or breaks with handling or little finger pressure
Moderate	Crumbles or breaks with considerable finger pressure
Strong	Will not crumble or break with finger pressure

TABLE 7 Criteria for Describing Structure

Description	Criteria
Stratified	Alternating layers of varying material or color with layers at least 6 mm thick; note thickness
Laminated	Alternating layers of varying material or color with the layers less than 6 mm thick; note thickness
Fissured	Breaks along definite planes of fracture with little resistance to fracturing
Slickensided	Fracture planes appear polished or glossy, sometimes striated
Blocky	Cohesive soil that can be broken down into small angular lumps which resist further breakdown
Lensed	Inclusion of small pockets of different soils, such as small lenses of sand scattered through a mass of clay; note thickness
Homogeneous	Same color and appearance throughout

identification procedures described hereafter.

12. Preparation for Identification

12.1 The soil identification portion of this practice is based on the portion of the soil sample that will pass a 3-in. (75-mm) sieve. The larger than 3-in. (75-mm) particles must be removed, manually, for a loose sample, or mentally, for an intact sample before classifying the soil.

12.2 Estimate and note the percentage of cobbles and the percentage of boulders. Performed visually, these estimates will be on the basis of volume percentage.

NOTE 8—Since the percentages of the particle-size distribution in Test Method D 2487 are by dry weight, and the estimates of percentages for gravel, sand, and fines in this practice are by dry weight, it is recommended that the report state that the percentages of cobbles and boulders are by volume.

12.3 Of the fraction of the soil smaller than 3 in. (75 mm), estimate and note the percentage, by dry weight, of the gravel, sand, and fines (see Appendix X4 for suggested procedures).

NOTE 9—Since the particle-size components appear visually on the basis of volume, considerable experience is required to estimate the percentages on the basis of dry weight. Frequent comparisons with laboratory particle-size analyses should be made.

12.3.1 The percentages shall be estimated to the closest 5 %. The percentages of gravel, sand, and fines must add up to 100 %.

12.3.2 If one of the components is present but not in sufficient quantity to be considered 5 % of the smaller than 3-in. (75-mm) portion, indicate its presence by the term *trace*, for example, trace of fines. A trace is not to be considered in the total of 100 % for the components.

TABLE 8 Criteria for Describing Dry Strength

Description	Criteria
None	The dry specimen crumbles into powder with mere pressure of handling
Low	The dry specimen crumbles into powder with some finger pressure
Medium	The dry specimen breaks into pieces or crumbles with considerable finger pressure
High	The dry specimen cannot be broken with finger pressure. Specimen will break into pieces between thumb and a hard surface
Very high	The dry specimen cannot be broken between the thumb and a hard surface

13. Preliminary Identification

13.1 The soil is *fine grained* if it contains 50 ... fines. Follow the procedures for identifying fine-gra... of Section 14.

13.2 The soil is *coarse grained* if it contains less than ... fines. Follow the procedures for identifying coarse-gr... soils of Section 15.

14. Procedure for Identifying Fine-Grained Soils

14.1 Select a representative sample of the materi... examination. Remove particles larger than the No. 40 ... (medium sand and larger) until a specimen equival... about a handful of material is available. Use this spec... for performing the dry strength, dilatancy, and tough... tests.

14.2 *Dry Strength:*

14.2.1 From the specimen, select enough material to ... into a ball about 1 in. (25 mm) in diameter. Mold ... material until it has the consistency of putty, adding wat... necessary.

14.2.2 From the molded material, make at least three ... specimens. A test specimen shall be a ball of material ab... ½ in. (12 mm) in diameter. Allow the test specimens to ... in air, or sun, or by artificial means, as long as ... temperature does not exceed 60°C.

14.2.3 If the test specimen contains natural dry lum... those that are about ½ in. (12 mm) in diameter may be ... in place of the molded balls.

NOTE 10—The process of molding and drying usuall... higher strengths than are found in natural dry lumps of soil.

14.2.4 Test the strength of the dry balls or lumps ... crushing between the fingers. Note the strength as none, l... medium, high, or very high in accorance with the criteria ... Table 8. If natural dry lumps are used, do not use the res... of any of the lumps that are found to contain particles ... coarse sand.

14.2.5 The presence of high-strength water-soluble ... menting materials, such as calcium carbonate, may ca... exceptionally high dry strengths. The presence of calci... carbonate can usually be detected from the intensity of ... reaction with dilute hydrochloric acid (see 10.6).

14.3 *Dilatancy:*

14.3.1 From the specimen, select enough material to m... into a ball about ½ in. (12 mm) in diameter. Mold ... material, adding water if necessary, until it has a soft, but ... sticky, consistency.

14.3.2 Smooth the soil ball in the palm of one hand w... the blade of a knife or small spatula. Shake horizonta... striking the side of the hand vigorously against the ot... hand several times. Note the reaction of water appearing ... the surface of the soil. Squeeze the sample by closing ... hand or pinching the soil between the fingers, and note ...

TABLE 9 Criteria for Describing Dilatancy

Description	Criteria
None	No visible change in the specimen
Slow	Water appears slowly on the surface of the spe... shaking and does not disappear or disappears s... squeezing
Rapid	Water appears quickly on the surface of the specimen du... shaking and disappears quickly upon squeezing

TABLE 10 Criteria for Describing Toughness

Description	Criteria
Low	Only slight pressure is required to roll the thread near the plastic limit. The thread and the lump are weak and soft
Medium	Medium pressure is required to roll the thread to near the plastic limit. The thread and the lump have medium stiffness
High	Considerable pressure is required to roll the thread to near the plastic limit. The thread and the lump have very high stiffness

14.3.2 Describe the reaction as none, slow, or rapid in accordance with the criteria in Table 9. The reaction is the speed with which water appears while shaking, and disappears while squeezing.

14.4 *Toughness:*

14.4.1 Following the completion of the dilatancy test, the test specimen is shaped into an elongated pat and rolled by hand on a smooth surface or between the palms into a thread about 1/8 in. (3 mm) in diameter. (If the sample is too wet to roll easily, it should be spread into a thin layer and allowed to lose some water by evaporation.) Fold the sample threads and reroll repeatedly until the thread crumbles at a diameter of about 1/8 in. The thread will crumble at a diameter of 1/8 in. when the soil is near the plastic limit. Note the pressure required to roll the thread near the plastic limit. Also, note the strength of the thread. After the thread crumbles, the pieces should be lumped together and kneaded until the lump crumbles. Note the toughness of the material during kneading.

14.4.2 Describe the toughness of the thread and lump as low, medium, or high in accordance with the criteria in Table 10.

14.5 *Plasticity*—On the basis of observations made during the toughness test, describe the plasticity of the material in accordance with the criteria given in Table 11.

14.6 Decide whether the soil is an *inorganic* or an *organic* fine-grained soil (see 14.8). If inorganic, follow the steps given in 14.7.

14.7 *Identification of Inorganic Fine-Grained Soils:*

14.7.1 Identify the soil as a *lean clay*, CL, if the soil has medium to high dry strength, no or slow dilatancy, and medium toughness and plasticity (see Table 12).

14.7.2 Identify the soil as a *fat clay*, CH, if the soil has high to very high dry strength, no dilatancy, and high toughness and plasticity (see Table 12).

14.7.3 Identify the soil as a *silt*, ML, if the soil has no to low dry strength, slow to rapid dilatancy, and low toughness and plasticity, or is nonplastic (see Table 12).

14.7.4 Identify the soil as an *elastic silt*, MH, if the soil has low to medium dry strength, no to slow dilatancy, and low to medium toughness and plasticity (see Table 12).

NOTE 11—These properties are similar to those for a lean clay. However, the silt will dry quickly on the hand and have a smooth, silky feel when dry. Some soils that would classify as MH in accordance with the criteria in Test Method D 2487 are visually difficult to distinguish from lean clays, CL. It may be necessary to perform laboratory testing for proper identification.

14.8 *Identification of Organic Fine-Grained Soils:*

14.8.1 Identify the soil as an *organic soil*, OL/OH, if the soil contains enough organic particles to influence the soil properties. Organic soils usually have a dark brown to black color and may have an organic odor. Often, organic soils will change color, for example, black to brown, when exposed to the air. Some organic soils will lighten in color significantly when air dried. Organic soils normally will not have a high toughness or plasticity. The thread for the toughness test will be spongy.

NOTE 12—In some cases, through practice and experience, it may be possible to further identify the organic soils as organic silts or organic clays, OL or OH. Correlations between the dilatancy, dry strength, toughness tests, and laboratory tests can be made to identify organic soils in certain deposits of similar materials of known geologic origin.

14.9 If the soil is estimated to have 15 to 25 % sand or gravel, or both, the words "with sand" or "with gravel" (whichever is more predominant) shall be added to the group name. For example: "lean clay with sand, CL" or "silt with gravel, ML" (see Figs. 1a and 1b). If the percentage of sand is equal to the percentage of gravel, use "with sand."

14.10 If the soil is estimated to have 30 % or more sand or gravel, or both, the words "sandy" or "gravelly" shall be added to the group name. Add the word "sandy" if there appears to be more sand than gravel. Add the word "gravelly" if there appears to be more gravel than sand. For example: "sandy lean clay, CL", "gravelly fat clay, CH", or "sandy silt, ML" (see Figs. 1a and 1b). If the percentage of sand is equal to the percent of gravel, use "sandy."

TABLE 11 Criteria for Describing Plasticity

Description	Criteria
Nonplastic	A 1/8-in. (3-mm) thread cannot be rolled at any water content
Low	The thread can barely be rolled and the lump cannot be formed when drier than the plastic limit
Medium	The thread is easy to roll and not much time is required to reach the plastic limit. The thread cannot be rerolled after reaching the plastic limit. The lump crumbles when drier than the plastic limit
High	It takes considerable time rolling and kneading to reach the plastic limit. The thread can be rerolled several times after reaching the plastic limit. The lump can be formed without crumbling when drier than the plastic limit

15. Procedure for Identifying Coarse-Grained Soils (Contains less than 50 % fines)

15.1 The soil is a *gravel* if the percentage of gravel is estimated to be more than the percentage of sand.

15.2 The soil is a *sand* if the percentage of gravel is estimated to be equal to or less than the percentage of sand.

15.3 The soil is a *clean gravel* or *clean sand* if the percentage of fines is estimated to be 5 % or less.

15.3.1 Identify the soil as a *well-graded gravel*, GW, or as a *well-graded sand*, SW, if it has a wide range of particle sizes and substantial amounts of the intermediate particle sizes.

15.3.2 Identify the soil as a *poorly graded gravel*, GP, or as a *poorly graded sand*, SP, if it consists predominantly of one size (uniformly graded), or it has a wide range of sizes with

TABLE 12 Identification of Inorranic Fine-Grained Soils from Manual Tests

Soil Symbol	Dry Strength	Dilatancy	Toughness
ML	None to low	Slow to rapid	Low or thread cannot be formed
CL	Medium to high	None to slow	Medium
MH	Low to medium	None to slow	Low to medium
CH	High to very high	None	High

some intermediate sizes obviously missing (gap or skip graded).

15.4 The soil is either a *gravel with fines* or a *sand with fines* if the percentage of fines is estimated to be 15 % or more.

15.4.1 Identify the soil as a *clayey gravel*, GC, or a *clayey sand*, SC, if the fines are clayey as determined by the procedures in Section 14.

15.4.2 Identify the soil as a *silty gravel*, GM, or a *silty sand*, SM, if the fines are silty as determined by the procedures in Section 14.

15.5 If the soil is estimated to contain 10 % fines, give the soil a dual identification using two group symbols.

15.5.1 The first group symbol shall correspond to a clean gravel or sand (GW, GP, SW, SP) and the second symbol shall correspond to a gravel or sand with fines (GC, GM, SC, SM).

15.5.2 The group name shall correspond to the first group symbol plus the words "with clay" or "with silt" to indicate the plasticity characteristics of the fines. For example: "well-graded gravel with clay, GW-GC" or "poorly graded sand with silt, SP-SM" (see Fig. 2).

15.6 If the specimen is predominantly sand or gravel but contains an estimated 15 % or more of the other coarse-grained constituent, the words "with gravel" or "with sand" shall be added to the group name. For example: "poorly graded gravel with sand, GP" or "clayey sand with gravel, SC" (see Fig. 2).

15.7 If the field sample contains any cobbles or boulders, or both, the words "with cobbles" or "with cobbles and boulders" shall be added to the group name. For example: "silty gravel with cobbles, GM."

16. Report

16.1 The report shall include the information as to origin, and the items indicated in Table 13.

NOTE 13—*Example: Clayey Gravel with Sand and Cobbles, GC*—About 50 % fine to coarse, subrounded to subangular gravel; about 30 % fine to coarse, subrounded sand; about 20 % fines with medium plasticity, high dry strength, no dilatancy, medium toughness; weak reaction with HCl; original field sample had about 5 % (by volume) subrounded cobbles, maximum dimension, 150 mm.

In-Place Conditions—Firm, homogeneous, dry, brown

Geologic Interpretation—Alluvial fan

NOTE 14—Other examples of soil descriptions and identificati[...] given in Appendixes X1 and X2.

NOTE 15—If desired, the percentages of gravel, sand, ar[...] be stated in terms indicating a range of percentages, as follo[...]

Trace—Particles are present but estimated to be less than 5 %

Few—5 to 10 %

Little—15 to 25 %

Some—30 to 45 %

Mostly—50 to 100 %

16.2 If, in the soil description, the soil is identified us[...] classification group symbol and name as described in[...] Method D 2487, it must be distinctly and clearly stated i[...] forms, summary tables, reports, and the like, that the sy[...] and name are based on visual-manual procedures.

17. Precision and Bias

17.1 This practice provides qualitative information [...] therefore, a precision and bias statement is not applica[...]

TABLE 13 Checklist for Description of Soils

1. Group name
2. Group symbol
3. Percent of cobbles or boulders, or both (by volume)
4. Percent of gravel, sand, or fines, or all three (by dry weight)
5. Particle-size range:
   - Gravel—fine, coarse
   - Sand—fine, medium, coarse
6. Particle angularity: angular, subangular, subrounded, rounded
7. Particle shape: (if appropriate) flat, elongated, flat and elongated
8. Maximum particle size or dimension
9. Hardness of coarse sand and larger particles
10. Plasticity of fines: nonplastic, low, medium, high
11. Dry strength: none, low, medium, high, very high
12. Dilatancy: none, slow, rapid
13. Toughness: low, medium, high
14. Color (in moist condition)
15. Odor (mention only if organic or unusual)
16. Moisture: dry, moist, wet
17. Reaction with HCl: none, weak, strong

For intact samples:

18. Consistency (fine-grained soils only): very soft, soft, firm, hard, very h[...]
19. Structure: stratified, laminated, fissured, slickensided, lensed, h[...]geneous
20. Cementation: weak, moderate, strong
21. Local name
22. Geologic interpretation
23. Additional comments: presence of roots or root holes, presence o[...] gypsum, etc., surface coatings on coarse-grained particles, cav[...] sloughing of auger hole or trench sides, difficulty in augering or exca[...] etc.

APPENDIXES

(Nonmandatory Information)

X1. EXAMPLES OF VISUAL SOIL DESCRIPTIONS

X1.1 The following examples show how the information required in 16.1 can be reported. The information that is included in descriptions should be based on individual circumstances and need.

X1.1.1 *Well-Graded Gravel with Sand (GW)*—About 75 % fine to coarse, hard, subangular gravel; about 25 % fine to coarse, hard, subangular sand; trace of fines; maximum size, 75 mm, brown, dry; no reaction with HCl.

X1.1.2 *Silty Sand with Gravel (SM)*—About 60 % [...] dominantly fine sand; about 25 % silty fines with [...] plasticity, low dry strength, rapid dilatancy, and low tou[...]ness; about 15 % fine, hard, subrounded gravel, a [...] gravel-size particles fractured with hammer blow; m[...] size, 25 mm; no reaction with HCl (Note—Field sa[...] smaller than recommended).

In-Place Conditions—Firm, stratified and contains le[...]

(silt 1 to 2 in. (25 to 50 mm) thick, moist, brown to gray; in-place density 106 lb/ft^3; in-place moisture 9 %.

X1.1.3 *Organic Soil (OL/OH)*—About 100 % fines with low plasticity, slow dilatancy, low dry strength, and low toughness; wet, dark brown, organic odor; weak reaction with HCl.

X1.1.4 *Silty Sand with Organic Fines (SM)*—About 75 % fine to coarse, hard, subangular reddish sand; about 25 % organic and silty dark brown nonplastic fines with no dry strength and slow dilatancy; wet; maximum size, coarse sand; weak reaction with HCl.

X1.1.5 *Poorly Graded Gravel with Silt, Sand, Cobbles and Boulders (GP-GM)*—About 75 % fine to coarse, hard, subrounded to subangular gravel; about 15 % fine, hard, subrounded to subangular sand; about 10 % silty nonplastic fines; moist, brown; no reaction with HCl; original field sample had about 5 % (by volume) hard, subrounded cobbles and a trace of hard, subrounded boulders, with a maximum dimension of 18 in. (450 mm).

X2. USING THE IDENTIFICATION PROCEDURE AS A DESCRIPTIVE SYSTEM FOR SHALE, CLAYSTONE, SHELLS, SLAG, CRUSHED ROCK, AND THE LIKE

X2.1 The identification procedure may be used as a descriptive system applied to materials that exist in-situ as shale, claystone, sandstone, siltstone, mudstone, etc., but convert to soils after field or laboratory processing (crushing, slaking, and the like).

X2.2 Materials such as shells, crushed rock, slag, and the like, should be identified as such. However, the procedures used in this practice for describing the particle size and plasticity characteristics may be used in the description of the material. If desired, an identification using a group name and symbol according to this practice may be assigned to aid in describing the material.

X2.3 The group symbol(s) and group names should be placed in quotation marks or noted with some type of distinguishing symbol. See examples.

X2.4 Examples of how group names and symbols can be incorporated into a descriptive system for materials that are not naturally occurring soils are as follows:

X2.4.1 *Shale Chunks*—Retrieved as 2 to 4-in. (50 to 100-mm) pieces of shale from power auger hole, dry, brown, no reaction with HCl. After slaking in water for 24 h, material identified as "Sandy Lean Clay (CL)"; about 60 % fines with medium plasticity, high dry strength, no dilatancy, and medium toughness; about 35 % fine to medium, hard sand; about 5 % gravel-size pieces of shale.

X2.4.2 *Crushed Sandstone*—Product of commercial crushing operation; "Poorly Graded Sand with Silt (SP-SM)"; about 90 % fine to medium sand; about 10 % nonplastic fines; dry, reddish-brown, strong reaction with HCl.

X2.4.3 *Broken Shells*—About 60 % gravel-size broken shells; about 30 % sand and sand-size shell pieces; about 10 % fines; "Poorly Graded Gravel with Sand (GP)."

X2.4.4 *Crushed Rock*—Processed from gravel and cobbles in Pit No. 7; "Poorly Graded Gravel (GP)"; about 90 % fine, hard, angular gravel-size particles; about 10 % coarse, hard, angular sand-size particles; dry, tan; no reaction with HCl.

X3. SUGGESTED PROCEDURE FOR USING A BORDERLINE SYMBOL FOR SOILS WITH TWO POSSIBLE IDENTIFICATIONS.

X3.1 Since this practice is based on estimates of particle size distribution and plasticity characteristics, it may be difficult to clearly identify the soil as belonging to one category. To indicate that the soil may fall into one of two possible basic groups, a borderline symbol may be used with the two symbols separated by a slash. For example: SC/CL or CL/CH.

X3.1.1 A borderline symbol may be used when the percentage of fines is estimated to be between 45 and 55 %. One symbol should be for a coarse-grained soil with fines and the other for a fine-grained soil. For example: GM/ML or CL/SC.

X3.1.2 A borderline symbol may be used when the percentage of sand and the percentage of gravel are estimated to be about the same. For example: GP/SP, SC/GC, GM/SM. It is practically impossible to have a soil that would have a borderline symbol of GW/SW.

X3.1.3 A borderline symbol may be used when the soil could be either well graded or poorly graded. For example: GW/GP, SW/SP.

X3.1.4 A borderline symbol may be used when the soil could either be a silt or a clay. For example: CL/ML, CH/MH, SC/SM.

X3.1.5 A borderline symbol may be used when a fine-grained soil has properties that indicate that it is at the boundary between a soil of low compressibility and a soil of high compressibility. For example: CL/CH, MH/ML.

X3.2 The order of the borderline symbols should reflect similarity to surrounding or adjacent soils. For example: soils in a borrow area have been identified as CH. One sample is considered to have a borderline symbol of CL and CH. To show similarity, the borderline symbol should be CH/CL.

X3.3 The group name for a soil with a borderline symbol should be the group name for the first symbol, except for:

CL/CH lean to fat clay
ML/CL clayey silt
CL/ML silty clay

X3.4 The use of a borderline symbol should not be used indiscriminately. Every effort shall be made to first place the soil into a single group.

X4. SUGGESTED PROCEDURES FOR ESTIMATING THE PERCENTAGES OF GRAVEL, SAND, AND FINES IN A SOIL SAMPLE

X4.1 *Jar Method*—The relative percentage of coarse- and fine-grained material may be estimated by thoroughly shaking a mixture of soil and water in a test tube or jar, and then allowing the mixture to settle. The coarse particles will fall to the bottom and successively finer particles will be deposited with increasing time; the sand sizes will fall out of suspension in 20 to 30 s. The relative proportions can be estimated from the relative volume of each size separate. This method should be correlated to particle-size laboratory determinations.

X4.2 *Visual Method*—Mentally visualize the gravel size particles placed in a sack (or other container) or sacks. Then, do the same with the sand size particles and the fines. Then, mentally compare the number of sacks to estimate the percentage of plus No. 4 sieve size and minus No. 4 sieve size present. The percentages of sand and fines in the minus sieve size No. 4 material can then be estimated from the wash test (X4.3).

X4.3 *Wash Test (for relative percentages of sand and fines)*—Select and moisten enough minus No. 4 sieve size material to form a 1-in (25-mm) cube of soil. Cut the cube in half, set one-half to the side, and place the other half in a small dish. Wash and decant the fines out of the material in the dish until the wash water is clear and then compare the two samples and estimate the percentage of sand and fines. Remember that the percentage is based on weight, not volume. However, the volume comparison will provide a reasonable indication of grain size percentages.

X4.3.1 While washing, it may be necessary to break down lumps of fines with the finger to get the correct percentages.

Water Well Geophysical Logs

4th Edition

Compiled By
Welenco, Incorporated

CONTENTS

1

INTRODUCTION

Today's tremendous and ever-increasing demands for water for suburban homes, for industries, for modern farming and for expanding cities have rendered yesterday's hit-and-miss methods of water seeking hopelessly inadequate. The effective investigation of underground water in any area requires (1) locating the water-bearing formations; (2) determining their water quality and (3) estimating their yield. Although surface exploration methods can be used to obtain general geological information on the area, only drilling, logging and testing of wells will accurately solve these problems.

The geophysical logs commonly run in water wells are similar in every respect to those run in oil and gas wells. In 1927, what would become the widest application of electrical surveying was attempted: the electrical surveying of a borehole by running a probe attached to the end of a cable into the well bore. Now, nearly all wells drilled for gas and oil along with a goodly number drilled for water are systematicaly *logged.* It is not surprising that, pursuant to the federal Clean Water Act, many California counties now require that logs be run under conditions where waters of different qualities may be encountered during drilling.

The purpose of this paper is to provide an explanation of some of the more commonly used geophysical logging techniques, how they work and what can be done with them to enhance the search for and recovery of more water.

Chart I-1 lists the tools that are generally available to the water well industry and how they are used in solving a variety of problems. Some of these tools can be used in both open and cased hole surveys, while others are restricted to use in open holes only because they depend on electrical signals that are short circuited by steel casing. The tools listed are run into wells on an armored cable which surrounds from one to seven insulated copper conductors. The tools which have electronics in the downhole sonde usually can be run on a cable that has one conductor, while those that have multiple contact points on the downhole sonde and no electronics downhole require one conductor for each measuring contact and are run on cables with four to seven conductors. Figure I-1 is a block diagram of the logging equipment used to obtain the logs described in this paper. The equipment is usually truck mounted and may make use of a very short, small diameter cable or, in the case of equipment also used for logging oil wells, be mounted in a large truck with 30,000 feet of heavy cable.

LOG TYPE OR DEVICE	CORRELATION	LITHOLOGY	BED THICKNESS	CLAY & SHALE CONTENT	TOTAL POROSITY	EFFECTIVE POROS	BULK DENSITY	WATER TABLE	CHEMICAL PHYS ICAL PROPERTIES	MOISTURE CONTENT	INFILTRATION	DIRECTION, VELO CITY GRD. WATER	DISPERSION, DILUT	SOURCE & MOVEMENT OF WATER IN WELL	CEMENTING	WELL CONSTRUCTION	CASING CORROSION	CASING LEAKS OR PLUGGING	HOLE DIAMETER	DEPTH CONTROL	DIP AND STR. OF FORMATIONS	FISH LOCATION	HOLE INCLINATION	COST RANG
SPONTANEOUS POTENTIAL	○	○	○	○					○															$585-2,400
SHORT NORMAL	○	○	○	○																				Part of abo
LONG NORMAL	○	○		○		○		○																Part of abov
LONG LATERAL		○		○		○																		Part of abov
INDUCTION LOG	○	○	○	○																				$2,400-2,700
MICROLOG		○	○	○																				$2,200-2,400
CALIPER LOG																●	●		○ ●					$500-1,800
GAMMA RAY LOG	○ ●	○ ●	○ ●	○ ●																				$450-1,800
* NEUTRON LOG	○ ●	○ ●	○ ●	○ ●	○ ●			○ ●		○ ●	○ ●													$700-1,800
* SPACED NEUTRON LOG	○ ●	○ ●	○ ●	○ ●	○ ●	○				○ ●	○ ●													$2,400-2,600
* DENSITY LOG		○ ●		○ ●			○ ●								●	●								$2,400
SONIC LOG	○ ●	○ ●			○										●									$2,400-3,100
TEMPERATURE LOG (DIFFERENTIAL)											●	○ ●	●	○ ●	●			●						$650-1,500
DIPMETER																					○		○	$4,000-4,700
SIDEWALL CORES	○	○		○	○	○	○		○															10 Cores $2.
FLOWMETER LOG												○ ●		●										$600-1,800
FLUID CONDUCTIVITY									●				●											$650-1,500
DOWNHOLE CAMERA	○	○	○					○ ●						●		●	●	●		●		○ ●		$450-1,000
COLLAR LOCATOR																				●		○		$500-1,600
DIRECTIONAL SURVEY																							○	$1,000-2,200

Services marked with an asterisk (*) require the use of radioactive material and may not be run on water wells in California. This is the only state with such a regulation.

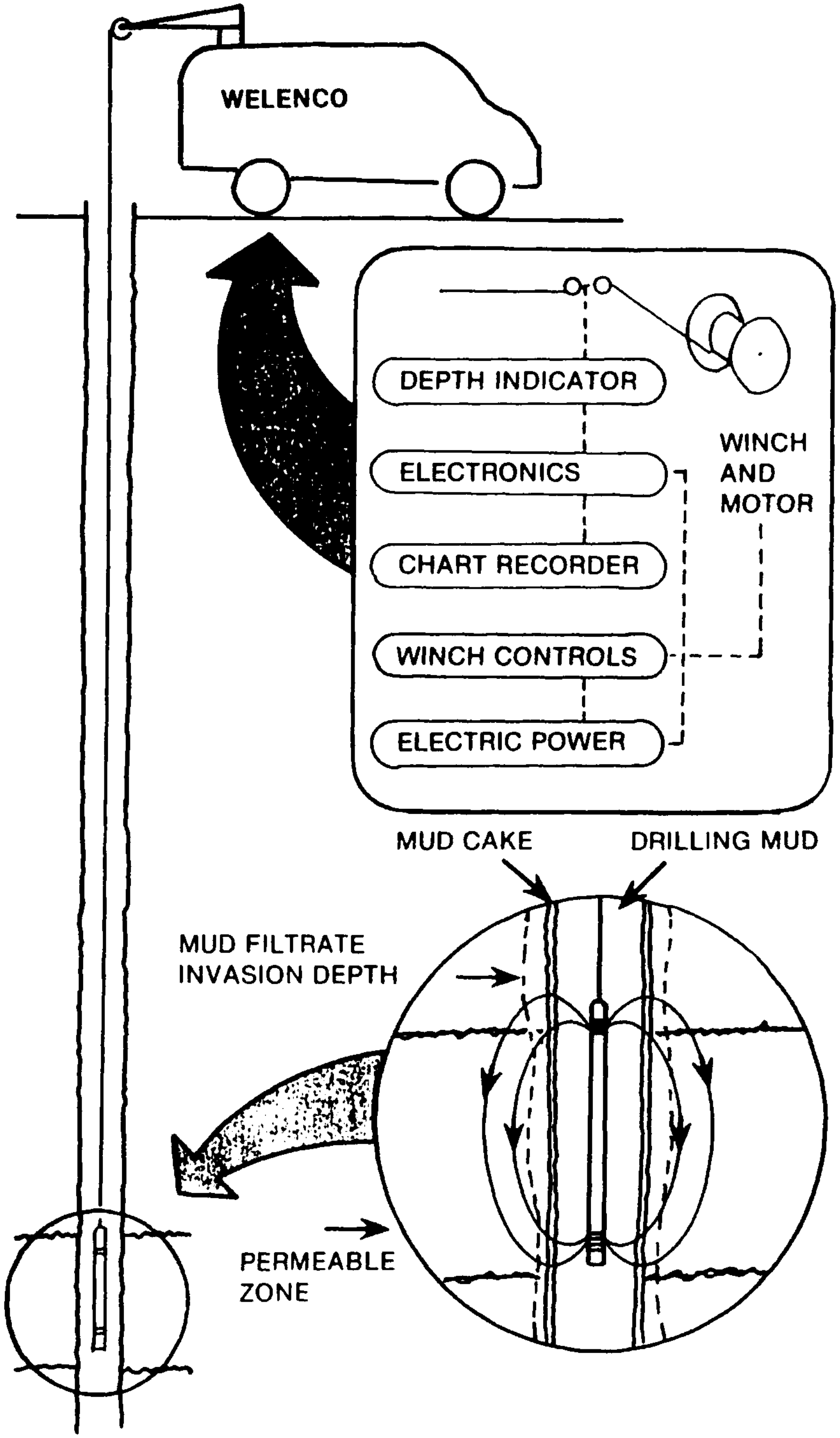


Figure I-1
Schematic of Geophysical Well Logging System

In order to obtain the greatest amount of information from a logging program, some pre-planning is definitely in order. It has been stated that log interpretation is more of an art than a science because different phenomena can cause similar log responses. For that reason it is imperative that the proper logs be run in any given situation, that the logs be properly calibrated and presented, that necessary associated information be obtained and tabulated and that the analysis of these logs be made by an analyst familiar with the area. For optimum information from an electric log, borehole geometry and some driiing fluid control should be considered. Logging tool sizes and access to well bores must be taken into account for some of the logs that might be run during the producing life of a well. Proper planning is the only way to obtain the greatest benefit from logs for the least expense.

The cardinal problem at the well is what to do with the hole you have just drilled. In few cases can the operator simply run a log and solve all his problems. To be of any great value, the log must distinguish between non-productive and possible productive formations. In wildcat areas, aside from indicating clear cut dry holes, all that should be expected of the initial log by itself is that it form a basis for wisely and economically selecting the various auxilliary evaluation or testing methods that may be necessary for deciding to pass up a dry hole or setting pipe in a productive well. Proper evaluation of the initial electric log may greatly reduce the number of unknowns and save unnecessary and costly mistakes. The spending of a few hours on the study of the log and other available information at the well is certainly not out of proportion to the total investment. Electric logs supply many known values from which to work.

Different wells call for different evaluation methods. Where drill cuttings and electric log studies may be all that are needed for a particular well, additional logs and studies may be necessary for evaluation of other wells. Today it is almost universally conceded that drill cutting study and an electric log are bare essentials for rotary holes. If the use of these two parameters answer all of your questions you need go no further. When there are still some unanswered questions, the question then arises, "how much information can I afford?"

Usually, the most difficult logs to interpret are those on which only a few sands are logged. Electric log interpretation is not really a science, but rather an art. Nature cannot be put into equations in a straightforward manner except through the intermediate process of data collection and statistical studies; and Geology is a natural science.

Not all problems encountered in log analysis are attributable to nature. The human being has his responsibilities too.

The logging engineer bears the largest responsibility. His measurements must be correct and he must be able to recognize that they are. So should the hydrogeologist who is going to interpret the results.

2

ELECTRIC LOGGING

Although primitive electric logs were made throughout Europe on a more or less experimental basis for many years, electric logging was not introduced on a commerical basis until 1929 when the Schlumberger brothers began running crude resistivity logs on oil wells near Alsace, France. These logs were an outgrowth of surface resistivity plots. In 1931, during the course of running one of these resistivity logs, the downhole current supply was accidentally disconnected and, instead of recording zero signal as expected, a signal was still present on the recording meter. The equipment was simply measuring a potential which was being generated in the borehole, hence the discovery of the Spontaneous Potential or SP which is still a part of every electric log run today.

The present day conventional electric log consists of the SP curve along with two or more resistivity curves of varying depths of investigation into the wall of the borehole, often implemented by several distinct types of electrode arrangements.

The electric log is an excellent correlation tool. This means that the electric log gives a good indication of the general type of material of which each bed is composed (sand, clay, limestone, etc.) as well as exactly where they are located in depth relative to some point at the surface. This, in turn, allows many beds to be recognized by some commonly-used name and to be fitted into the known geologic sequence in the area. Also it is possible to determine the amount of pore space contained in the formation and the amount and kind of fluids contained in this pore space. How well the porosity and fluid information can be determined depends on how accurately the interpreter knows a number of factors in the well, such as mud resistivity, temperature, formation water resistivity, depth of invasion into the formation by the mud filtrate, etc. The value of these determinations is also affected by how well the interpreter can correct certain inherent errors caused by geometric factors such as sonde diameter, borehole diameter and bed thickness. The amount of information that can be derived from logs is generally a function of the background information available, the number of different types of logs run and the experience of the analyst. Electric log interpretation is not really a science, but rather an art. Nature cannot be put into equations in a straight-forward manner except through the intermediate process of data collection and statistical studies.

The format for log presentation was established many years ago by the

American Petroleum Institute (API) in order that all of the service companies record similar electrical measurements on a standard width chart so that direct comparisons could be made of logs. In addition, log headings were standardized with pertinent information in the same order for every service company. In the absence of a better system, water well logs are usually presented in the same format. For electric logs, the standard log is 8¼ inches wide and has three vertical columns each 2½ inches wide divided into 10 divisions. The left hand column is separated from the other two by a ¾ inch column in which depths are recorded. The SP is recorded in the left hand track, the short and long normal resistivity curves are recorded in the center track and are differentiated by recording the long normal as a dotted trace. The far right column is used to record either a long lateral curve or a point resistance detail curve.

The Spontaneous Potential Curve

It should be understood that *potential* is just another term for voltage. Thus, a common flashlight cell generates a potential of 1.5 volts. Potentials of much smaller magnitude are encountered in the well bore. In fact, these potentials are so small that the volt is too large a unit for conveniently measuring them, so a much smaller unit called a millivolt is employed. A millivolt is 1/1000 of a volt or 0.001 volt. Figure II-1 shows a simplified SP circuit.

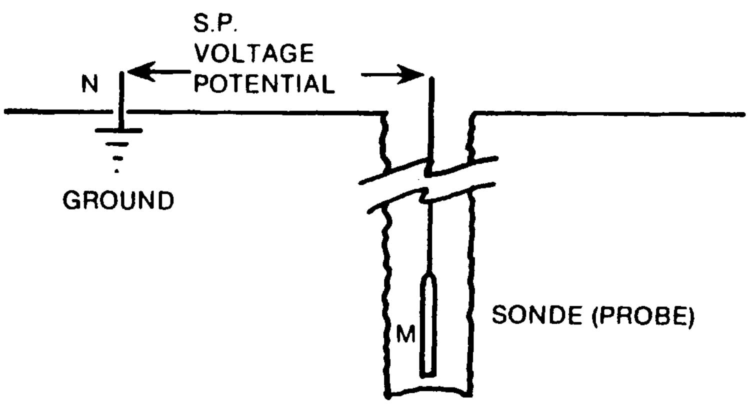


Figure II-1
Simplified S P Circuit

The SP is mainly used for geologic correlation, for finding bed thickness, for separating non-porous from porous beds in shale-sandstone and shale-carbonate sequences. There are three connected media needed to generate the SP; a permeable bed having water in the pores, a clay or shale bed, and a boreho[illegible]ed with mud or water. Figure II-2 shows the current generated within t[illegible]three media. II-2-A shows a condition where formation water is

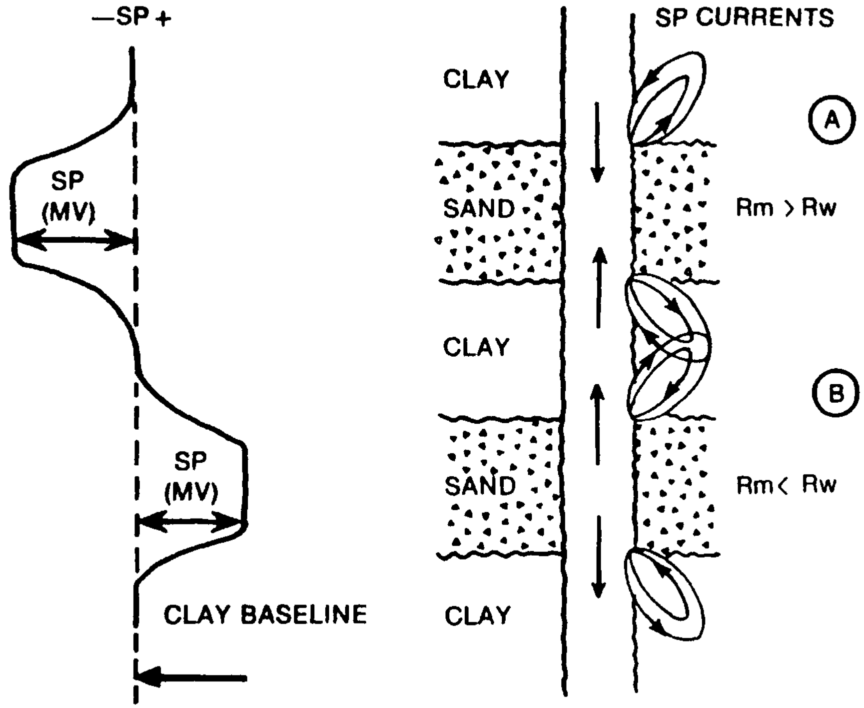


Figure II-2
Positive and Negative SP Curves Relative to Mud and Water Resistivities

less resistive (saltier) than the drilling mud. In II-2-B the formation water is more resistive (fresher) than the mud. The larger the resistivity difference, the larger the magnitude of the potential.

There are three methods by which potentials are spontaneously generated in mud filled holes. First, a potential can be generated by an electrolyte being forced under pressure through a pervious membrane, and is called a *streaming* potential. Second, a *liquid junction* potential is generated when two electrolytes with different concentrations and/or ions come in contact or are separated by a pervious membrane. The third, *shale* potential is generated by a diffusion mechanism.

Since streaming potentials are of little consequence in water wells, they will not be discussed here. Liquid junction potentials are generated when two electrolytes of different concentrations containing ions of different mobilities come in contact with each other or are separated by a pervious membrane. In the bore hole region these conditions exist. If the formation fluid is saltier than the fluid in the hole (mud or water), a normal occurrence, there will be an excess of ions in the formation fluid. Many of these ions, both positive and negative, will migrate or diffuse into the bore hole. Sodium chloride is normally the dominant chemical [illegible]pound in solution. Both sodium ions and chloride ions have an electri[illegible]arge. The c[illegible]s are of equal magnitude but of opposite sign. Sodium ions are positive and chloride ions are negative. Chloride ions, having greater mobility than sodium ions, move faster. Thus, there will always be more chloride ions in the borehole than there will be sodium ions. The fluid in the hole in front of a porous, permeable formation, containing saltier fluid than is in the hole, will always have an excess of negative ions and therefore a potential which is also negative with respect to its surroundings.

Shale potentials also are generated by a diffusion mechanism. However, in this case, the shale acts as a selectively permeable membrane, allowing the slower moving sodium ions to pass through into the borehole while holding back the negative chloride ions by electrostatic repulsion. Therefore, the fluid in the hole in front of a shale section, containing saltier fluid than is in the hole, will always have an excess of positive ions and also a potential which is positive relative to its surroundings. It is these differences of potential opposite shales and adjacent permeable formations which are recorded as the SP curve. Like the liquid junction potential, the shale potential becomes greater with a greater contrast in resistivity between the water in the borehole and the water in the formation. The total potential recorded is the sum of the liquid junction and shale potentials. The liquid junction potential makes up about 17 percent of the actual observed value while the shale potential contributes the other 83 percent.

The SP curve can be used with the proper charts and formulae to calculate the formation water resistivity. Other information needed to do the calculations includes the resistivity and temperature of the mud, resistivity and temperature of the mud filtrate, and the formation temperature.

The amplitude of the SP curve is mainly affected by the bed thickness in relation to the borehole diameter and by the bed resistivity in relation to the borehole mud resistivity. As the ratio of bed thickness to borehole diameter increases, full potential development is achieved and called Static SP (SSP). As the ratio is reduced, a correction factor is needed. Also, when the ratio of bed resistivity to mud resistivity is high, a correction factor is needed. A low bed to mud resistivity will allow full SP deflection.

The ions contained in the solutions (mud and formation water) and their concentrations also affect the SP curve. The presence of the divalent cations magnesium and calcium (Mg^{++}, Ca^{++}) cause an SP that looks saltier than it really is.

The calculation of electrical conductivity (EC) and total dissolved solids (TDS) requires several measurements, the use of charts and curves, and most important of all, adaptation and refinement for each geographic area.

Water Quality Calculation from the SP

Using the example log in Figure II-3 and the *Salinity-Resistivity* chart in Figure II-4 along with some appropriate formulas, we can show one of the methods used in the determination of water quality:

1. Obtain a circulated mud sample just before the drill pipe is pulled from the well. Measure the resistivity and temperature of the mud sample. R_m = 32.6 @ 63° F.

2. Using the mud press, obtain a mud filtrate sample. [illegible]sure the resistivity and temperature of the filtrate. R_{mf} 32.6 @ 6[illegible] F.
3. Convert R_{mf} at the measured temperature to is value at 77° F. using the chart in Figure II-4. R_{mf} = 26.5 @ 77° F.
4. Determine R_{mfe} @ 77° F. R_{mfe} = R_{mf} for NaCl muds. R_{mfe} = 0.85 R_{mf} for non-NaCl muds. This case is non-NaCl. R_{mfe} = 22.5 @ 77° F.
5. Determine the zones of interest from the electric log. In this case, we will study the sand just below 700 feet. SP = -6 MV.
6. For each zone of interest, determine R_{we} from the appropriate formula:

   NaCl mud and NaCl formation waters: $R_w = 10^{SP/70} \times R_{mf}$

   NcCl mud and non NaCl formation waters: $R_{we} = 10^{SP/70} \times R_{mf}$

   Non NaCl mud and non NaCl formation waters: $R_{we} = 10^{SP/70} \times R_{mfe}$

   $R_{we} = 10^{SP/70} \times R_{mfe}$

   $= 10^{-6/70} \times 22.5$

   $= 18.5$
7. Determine R_w @ 77° F.

   $R_w = R_{we}$ for NcCl formation waters

   $R_w = R_{we} \times 1.75$ for $NaHCO_3$ formation waters

   $R_w = 32.4$
8. Determine TDS @ 77° F. with the following formula:

   TDS in PPM = K/R_w Where K = 12,000 for $Ca(HCO_3)_2$ solutions

   K = 10,000 for $NaHCO_3$ solutions

   K = 6,700 for $MgSO_4$ solutions

   K = 5,300 for NaCl solutions

   K = 4,200 for $MgCl_2$ solutions

   TDS in PPM = 10,000/32.4 = 309 PPM

Since nature is never simple, we need to constantly upgrade our methods of interpretation by the inclusion of more and more information from nearby wells. You can see from the above formulae that a knowledge of ionic assemblages is essential to accurate interpretation. A laboratory analysis should be obtained of water from each completed well. The cost is very reasonable and will help the log analyst immeasurably in plotting geographical distributions.

The Resistivity Curves

Resistance is the opposition offered by a body to the passage of an electrical current through it. The unit of measurement is the *ohm*, and a body has a resistance of one ohm when a potential of one volt across it causes one ampere of current to flow.

Resistance is directly proportional to length (as the length is increased or decreased, the resistance is changed the same amount). On the other hand resistance is inversely proportional to cross sectional area (as the cross sectional area decreases, the resistance increases). Another term used in logging is *resistivity*, and it is a material's resistance per unit volume. The units of resistivity are ohm-meters squared per meter.

Unlike resistance, resistivity is not merely a characteristic of some

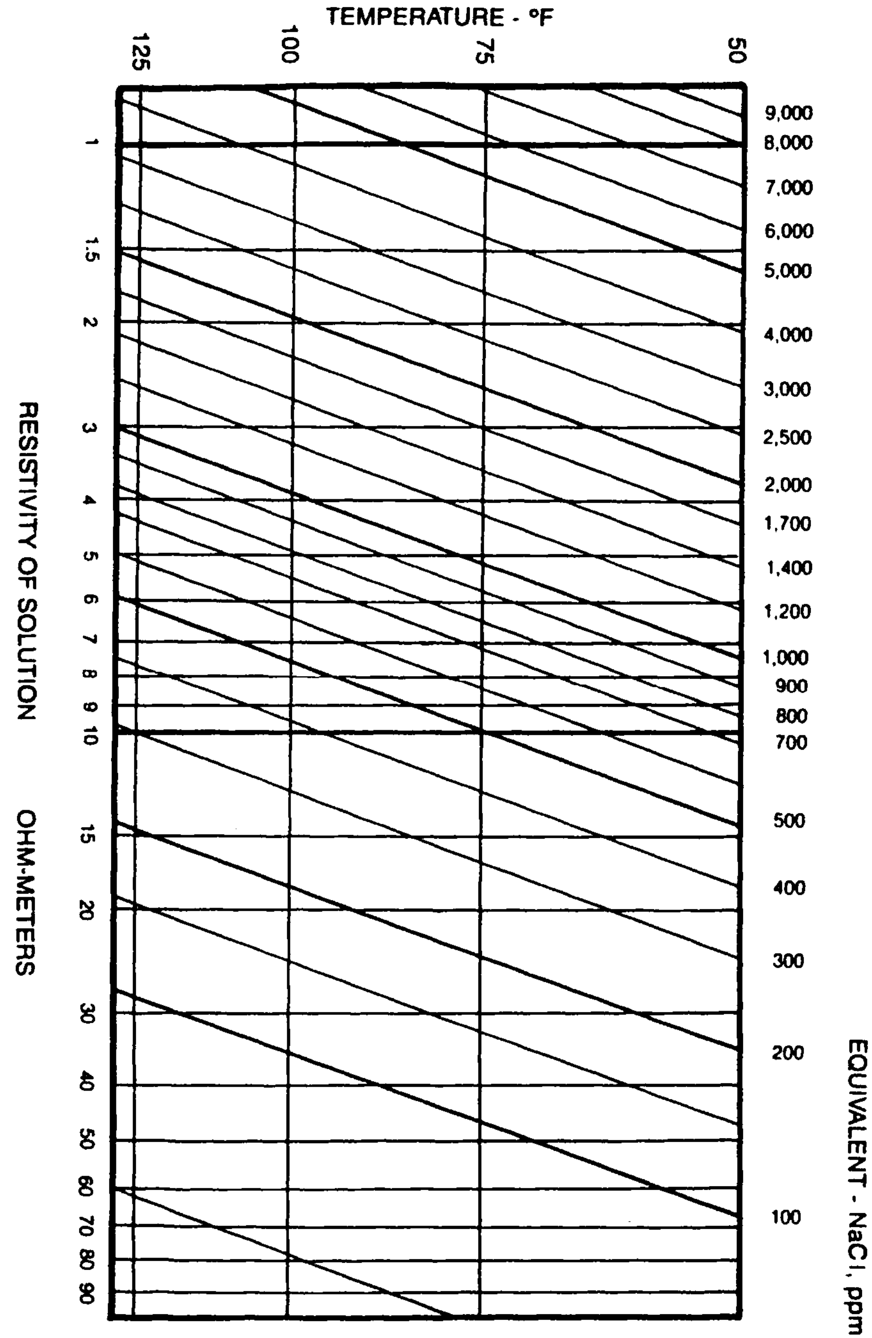


Figure II-4
Salinity - Resistivity - Fresh Waters

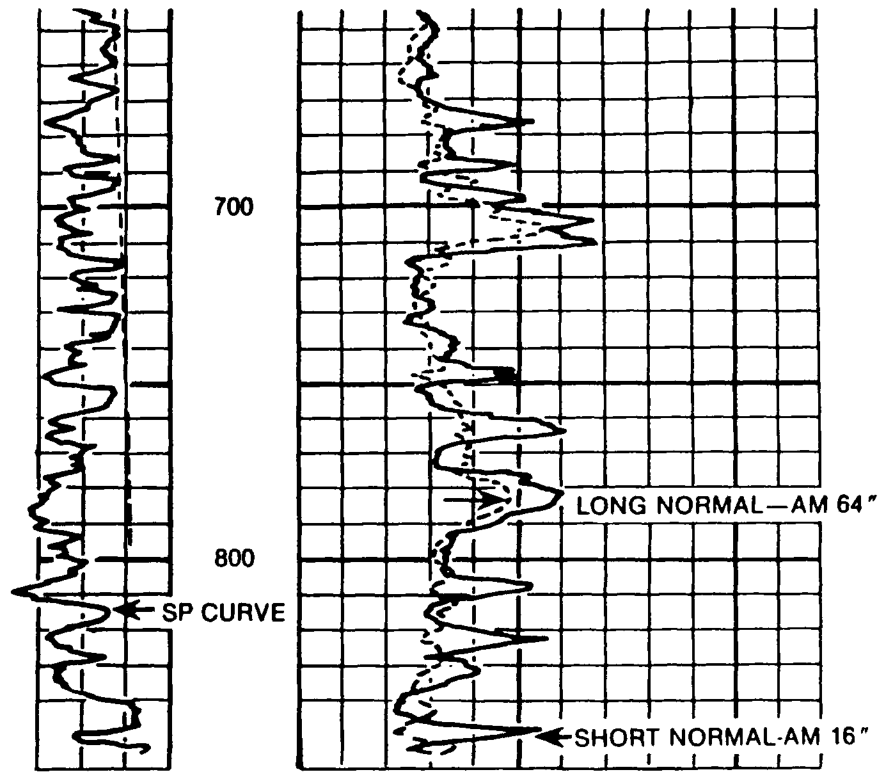


Figure II-3
Example - SP Curve Used For Water Quality Calculation

particular piece of a material, but is one of its basic physical properties, and is true of all pieces of that material at a given temperature and pressure.

All rock formations conduct electricity to a greater or lesser extent. Electrical conductivity is a measure of the ability of rocks to conduct electricity. Resistivity, on the other hand, measures the ability of rocks to oppose the flow of electricity. In fact, resistivity is the reciprocal of conductivity.

Unlike metallic conductivity (by electron flow) or semi-conductor conductivity (by electrons and holes), rock conductivity is due to the presence of ions of salt dissolved in the water filling the pore spaces of the rocks. Water samples containing dissolved salts are called solutions and we are mainly concerned with the electrolytic conductivity of solutions. The larger the ionic content, the larger the conductivity and, conversely, the smaller the resistivity. It is to be noted that perfectly pure distilled water is not a conductor at all; instead, it is a perfect insulator. Such a situation does not conform to reality since the purest waters contain at least traces of dissolved salts, which make them slightly conductive.

Table II-1
Typical Resistivities For Various Electrolytes

Electrolyte	Resistivity (ohm-Meters)
Brine	.04
Brackish water	.2 to .5
Sea Water	.2
Drilling mud	.04 to 5.00
Tap water	7 to 15
Distilled water	several hundred ohms

The conductivity of an electrolyte is, among other things which can be neglected for the time being, a function of two factors:

1. The salt concentration in the solution, that is the amount of dissolved salt in parts per million (ppm), or grains per gallon, etc.; the higher the concentration, the higher the conductivity.
2. The nature of the salt, or the nature of the ions; some ions being better conductors than others.

Figure II-5 indicates the conductivity of various salt solutions versus concentrations.

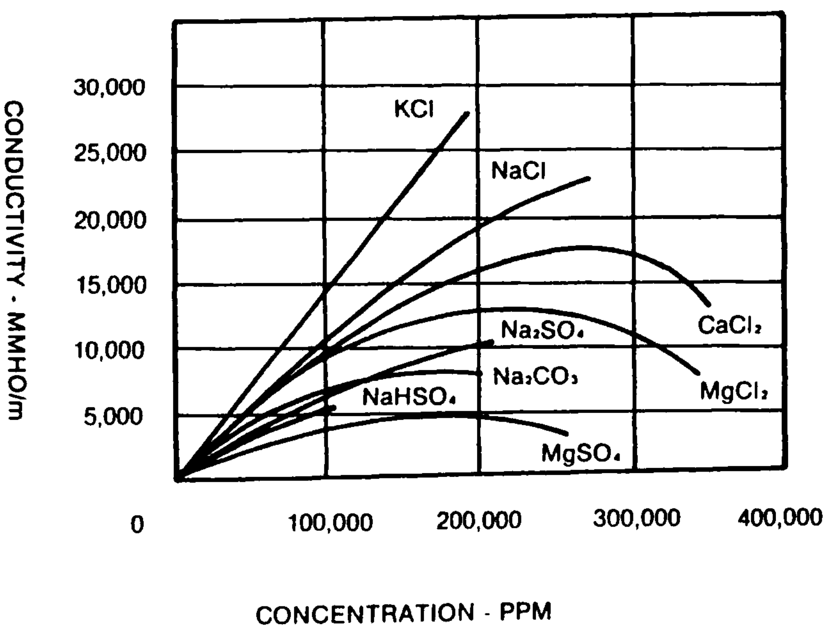


Figure II-5
Conductivity Versus Concentration For Salt Solutions at 18 C

Temperature also affects the resistivity of electrolytes. As the temperature increases, the resistivity of the electrolyte decreases. The chart of Figure II-4 indicates the magnitude of resistivity variations for sodium chloride solutions under variations in solution temperature. This chart also indicates the ion concentrations in parts per million (ppm).

Some rocks will conduct electricity through the interconnecting pore channels filled with formation water, which is an electrolytic solution and, therefore, is a conductive medium. In most cases of interest (shaly or clayey sands are the exceptions), the matrix surrounding the pores is non-conductive. The conductivity of a given volume of formation will be lower than that of an equal volume of the same water only. By the same token, an identical volume of pure matrix (no water) would have no conductivity (or infinite resistivity).

The early method of logging made use of a single monoelectrode probe, Figure II-6-A. An electric current was fed from the surface to the electrode. This current then spread from the electrode into the formation, returning to the surface and back to the current generator through a surface electrode return (a mud pit electrode, a casing clamp, a stake planted in the ground, etc.). The main shortcoming of the monoelectrode was the lack of depth of investigation. Very broadly, half of the measurement originates from a spherical shell which has a thickness equal to the radius of the electrode. It is obvious that this type of measurement will be highly influenced by the mud in the borehole. For this reason, this system has been superseded by the multi-electrode system.

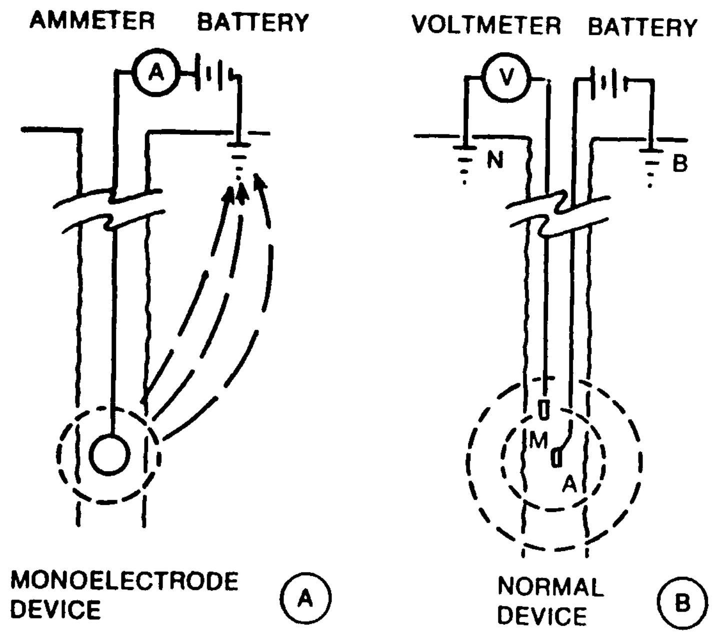


Figure II-6-A, B
Comparison — Monoelectrode Versus Normal Devices

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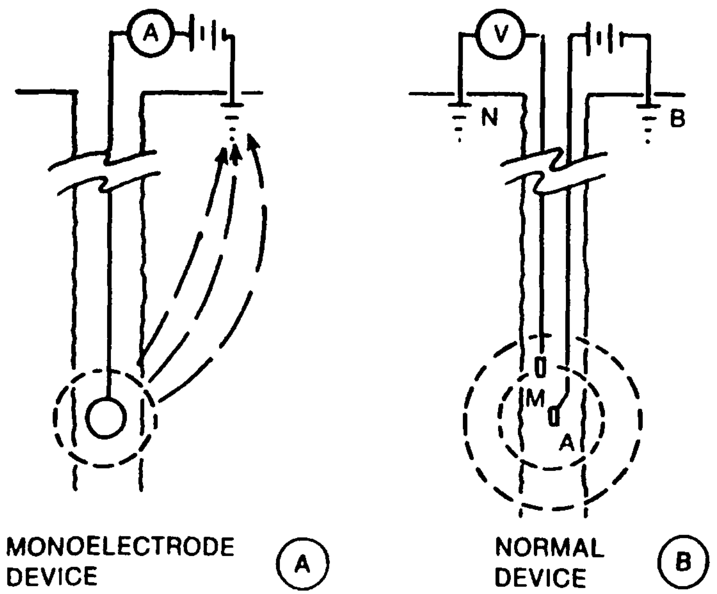


Figure II-6-A, B
Comparison — Monoelectrode Versus Normal Devices

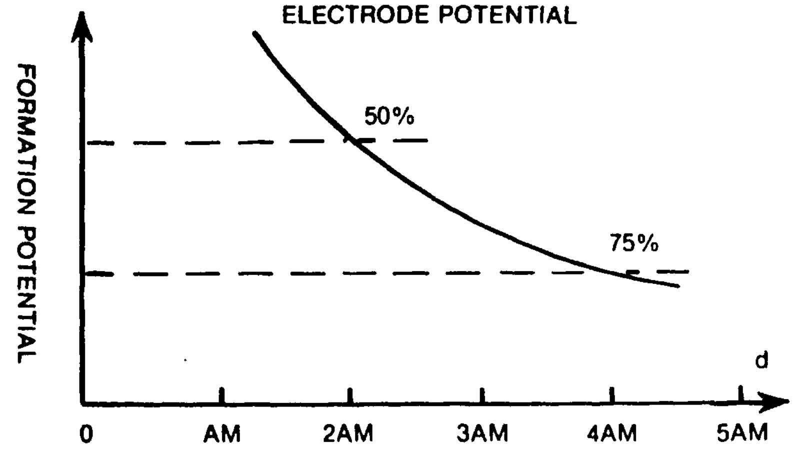


Figure II-7
Depth of Investigation of Normal Device

There are two general types of resistivity curves employed in electric logging; those of shallow penetration and those of deep penetration.

Curves of shallow penetration are those that measure, predominantly, the resistivity of the zone near the bore hole. This zone has, in varying degrees, some of its natural fluid displaced; as water or mud filtrate from the bore is forced into it by the pressure of drilling or by the weight of the fluid column. For this reason it is known as the *invaded zone*. Many factors influence the invasion process.

Since non-fractured shale has no permeability, there is no invasion in most shale beds, and resistivities are the same in uniform shales at any distance from the bore hole. Although the resistivities of hard non-porous beds are vastly different from those of shales, these beds are also uninvaded, and if they are uniform, their resistivities remain the same at any distance from the bore hole.

In permeable beds drilled with rotary tools using drilling mud, the porosity affects the depth the invaded zone extends from the bore hole. The shallowest invasion occurs in the highest porosities, and the deepest invasion in the lowest porosities.

Although there are specialized and complex penetration curves for measuring the resistivity of the invaded zone, the one most used is the 16-inch normal resistivity curve. The 16-inch curve is shown on the electric log graph as the solid curve in the center column. It is calibrated so that the right-hand edge of the depth-marking column represents 0 ohm M^2/M and resistivity increases with increasing deflection to the right.

Curves of deep penetration are those that measure, predominantly, the resistivity of a zone further away from the bore hole, and except for deep invasion, a zone largely beyond the invaded zone where conditions are still as they were before the well was drilled. The resistivity of the uninvaded zone is shown as the *true resistivity* of the bed. The true resistivity is useful in estimating the type and relative quantities of fluids contained in the pore space.

As was the case with shallow penetration curves, there are specialized and complex deep penetration curves for measuring or deriving true resistivity, but the one most used is the 64-inch normal resistivity curve. The 64-inch curve is shown on the electric log graph as the dotted curve in the center column. It is calibrated in exactly the same manner as the 16-inch normal resistivity curve and uses the same scale markings.

In rock with no continuous path of pore space through the rock, called non-connected porosity, the resistivity of the fluid does not greatly affect the total resistivity. Instead, the rock surrounding the fluid is the major influence on the resistivity reading that we get. The situation is equivalent to a current going through a series of resistors, and the total resistance is the sum of the separate resistances. With the standard electric log alone, we cannot distinguish between zero porosity and non-connected porosity.

The thickness of the bed we attempt to measure, also has a pronounced affect on the accuracy of the results. The amount of inaccuracy is dependent upon the comparison between the probe spacing and the bed thickness. When a resistive bed is thinner than the spacing of the normal device and is surrounded by beds of low resistivity, it will be recorded on the

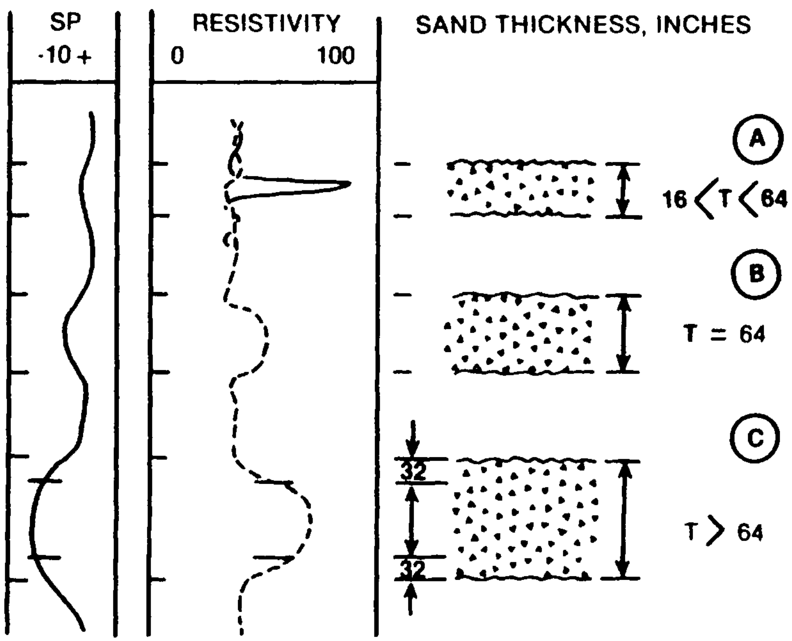


Figure II-8 A, B and C.
Examples - Bed Thickness.I. Versus Electrode Spacing For Normal Device, AM = 64 Inches

log as low resistivity. If this thin, resistive bed is between two low-resistivity shale beds, this erronious value will be even less than the resistivity of the shales. This phenomenon is known simply as a *reversal*. This can be illustrated by showing a highly-resistive bed thicker than the 16-inch short normal spacing, but thinner than the 64-inch long normal spacing. Under this condition the 64-inch resistivity curve will reverse and falsely indicate a low resistivity, since the bed is thinner than its spacing. This example is pictured in Figure II- 8-A.

When the thickness of a bed is equal to the spacing, the recording is almost flat and the bed is said to be of critical thickness. See Figure II- 8 -B.

If a bed had a thickness many times the spacing, the value recorded follows the pattern of the *regular* response. Normal resistivity curves always show resistive beds thinner than they actually are by an amount equal to the spacing. Half of this error is at the top boundary. This effect is pictured in Figure II- 8 -C.

Lateral Curve

With the lateral device we can measure the resistivity of the formation further from the hole than by the normal devices. The distance depends on the spacing of the electrodes. The lateral tool is a 3-electrode device (see Figure II- 9) comprised of two voltage measuring electrodes (M, N) and a current electrode (A). The two voltage measuring electrodes are close to each other but remotely located from the current electrode.

The effective measuring point of the lateral device is midway between the potential electrodes M and N and is labled O. The nominal spacing of the device is the distance from this midpoint O, to current electrode A and is called the AO spacing. Electric logs which include a lateral curve indicate the AO spacing on the log heading. Common AO spacings are in the neighborhood of 15 feet.

The lateral device measures the resistivity of a small volume of material far out in the formation without involving the material nearer the borehole, as the normal devices do. The dashed circle shows the *equipotential sphere* the tool measures. There are some particular responses that show up on the lateral logs. The following is an explanation of the responses.

First, in a thick resistive bed (several times the AO spacing) between two beds of low resistivity a response as in Figure II- 10-A occurs. As electrode A leaves the bed, a part of the resistive bed equal to the AO spacing is falsely indicated as having a low resistivity. From the bottom of this interval to the bottom of the bed, the resistivity indication increases to a value which is greater than the true resistivity. A good procedure for picking the true resistivity (R_T) from the lateral curve in thick, resistive beds is to choose the indicated value as shown in Figure II-10-A. It is to be noted that the lateral resistivity curve is not symmetrical, whereas the normal curves have symmetry.

As we make the resistive bed thinner, the peak deflection of the lateral curve exceeds the true resistivity by less and less, until when the bed thickness is 1½ times the AO spacing, the true resistivity may be chosen as the indication at a point 2/3 of the distance out on the slope, below a

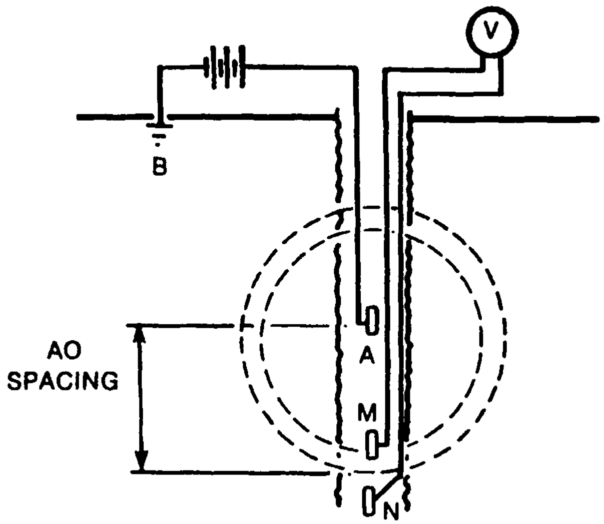


Figure II-9
Schematic Lateral Device

distance AO from the top of the bed. This choice is illustrated in Figure II-10-B.

When the bed thickness decreases to 1⅓ times the AO spacing, the peak response may be chosen as the true resistivity. Figure II-10-C shows this case. When the bed thickness reaches the AO spacing, the lateral device has its minimum response. Although the true resistivity can only be guessed at this *critical thickness*, the indication of the graph is likely about ¼ to ⅓ of the true resistivity. The response of the lateral device to a bed of critical thickness (thickness = AO) is shown in Figure II-10-D.

As the bed becomes thinner than the AP spacing, unlike the normal, the indicated resistivity from the lateral device increases, although the apparent resistivity never again reaches the true resistivity. With bed thicknesses of ¼ to ½ the AO spacing, the true resistivity is estimated by multiplying the peak value (R_{MAX}) in the bed by the resistivity of the adjacent shale (R_S) and dividing this product ($R_{MAX} \times R_S$) by the minimum value (R_{MIN}) below the thin bed. Figure II-10-E illustrates this procedure.

Several more peculiarities of the lateral device must be mentioned. Below beds which are thinner than the AO spacing, the lateral device falsely indicates a very low resistivity for a distance below the bed equal to the difference between the AO spacing and the bed thickness (AO – bed thickness). Because the lateral is incapable of indicating any high resistivities in this zone even if they exist, this zone is known as the *blind or dead zone*.

Another interesting phenomenon manifests itself below these beds, which are thinner than the AO spacing. At the botton of the dead zone, when the current electrode A is entering the top of the thin, resistive bed above, the resist[illegible]y indication begins to increase, and it continues to increase until

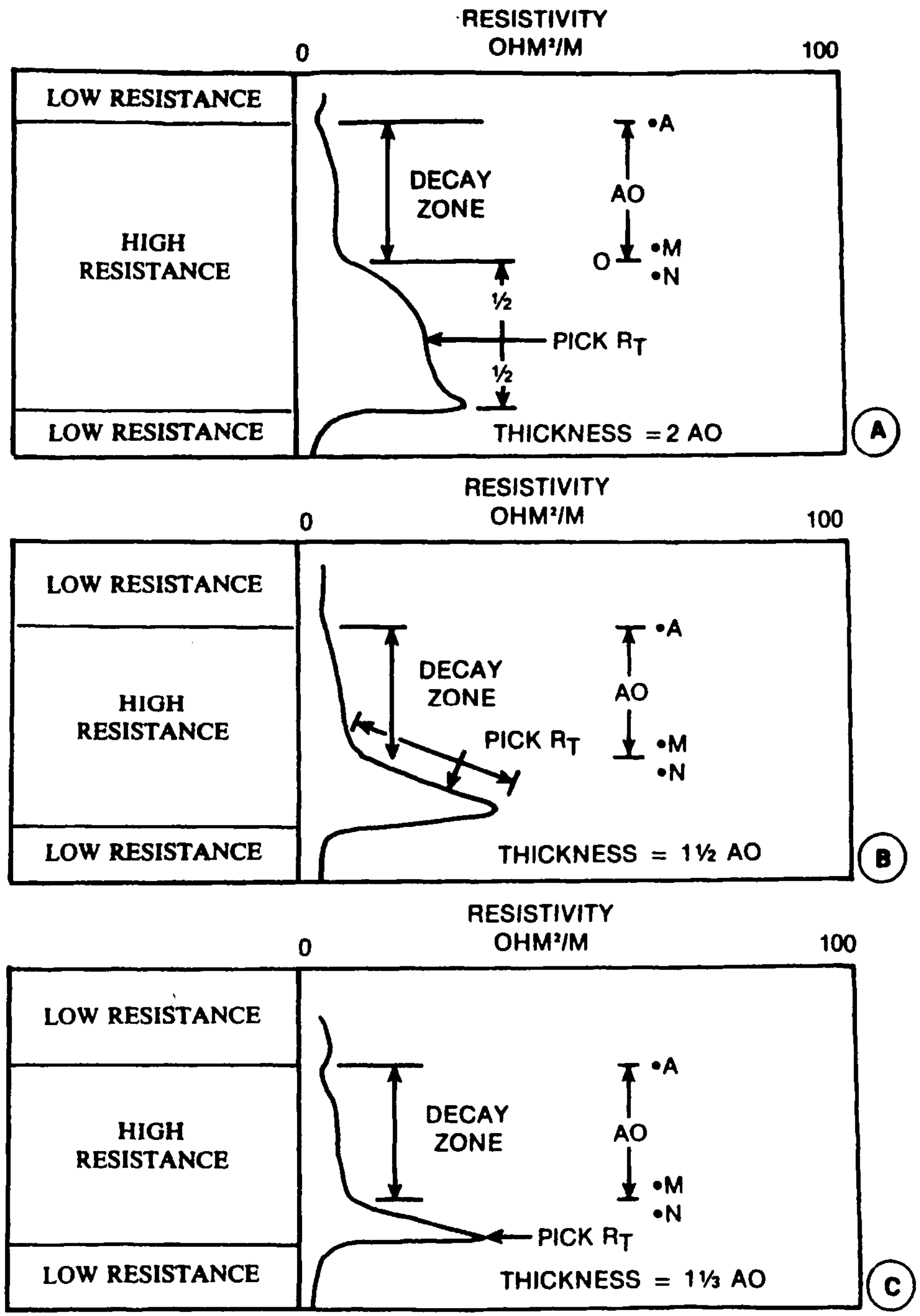


Figure II-10 - A, B and C
Example Bed Thickness
Versus Electrode Spacings
For Lateral Device

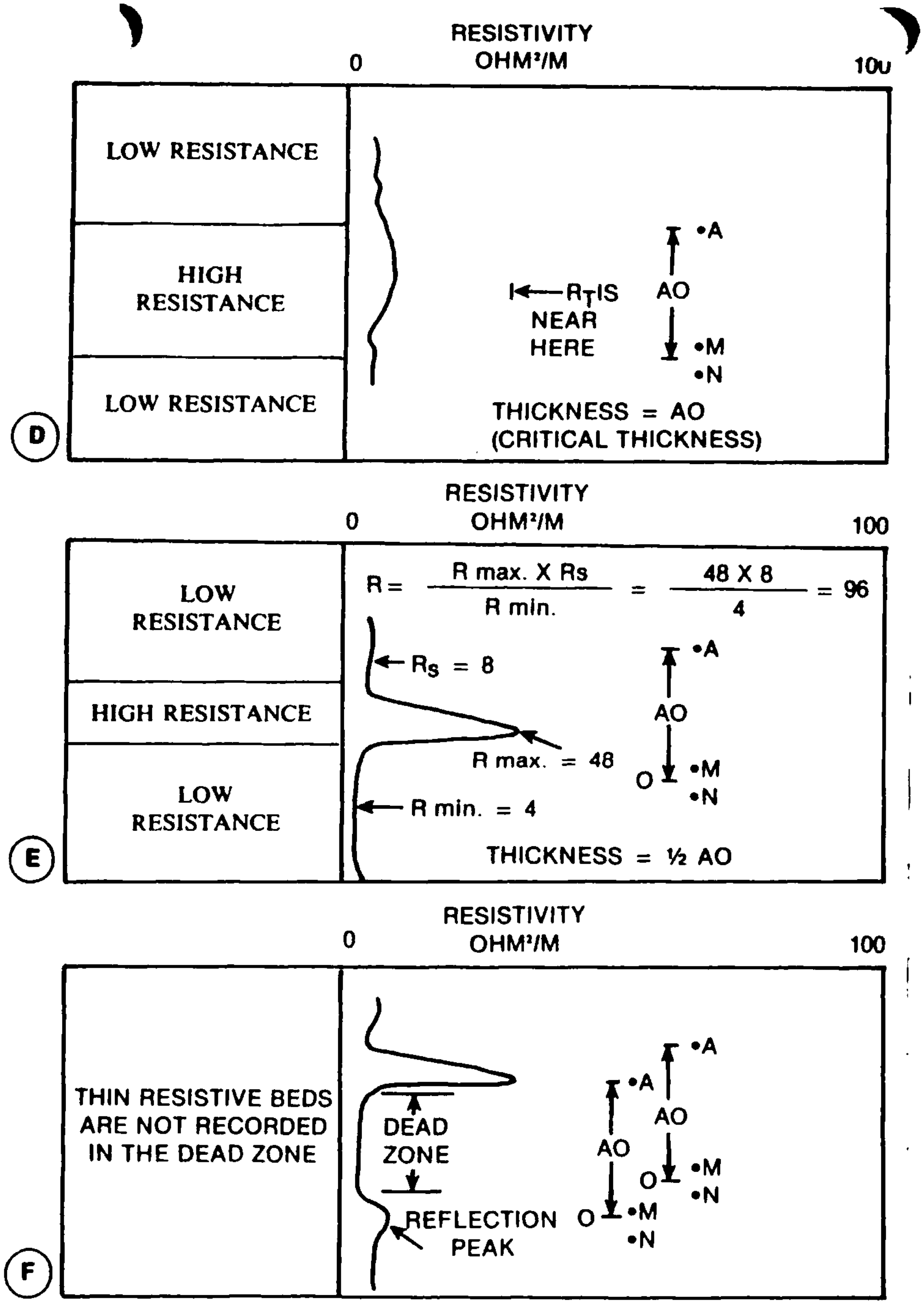


Figure II-10 - D, E and F
Example Bed Thickness
Versus Electrode Spacings
For Lateral Device

current electrode A leaves the bottom of the thin resistive bed above. This increase in indicated resistivity does not necessarily represent a formation resistivity change but is caused by the current electrode A passing through the thin resistive bed above. This false indication of increased resistivity is known as the *reflection peak*. Figure II-10-F points out these peculiarities.

We have shown that the lateral resistivity curve, even in homogeneous beds, has some peculiar responses. In sequences of beds and heterogeneous beds, the response may become so confusing as to be of little value.

Although, as mentioned, the lateral curve is often confusing and sometimes worthless, it does have several advantages. In extremely thick beds, it yields a relatively uninvaded value of true resistivity and, also for this reason, it is useful in estimating the extent of invasion existent in the long normal curve. Since the lateral does not reverse in thin beds, it permits an estimate of true resistivity of those beds.

Induction Electric Log (IEL)

The Induction Electric Log measures conductivity from alternating currents that are induced into the formation. It is very accurate for medium to low resistivity values (less than 50 ohm-meters) and where the ratio of resistivity of the mud filtrate to the resistivity of the formation water is 2.5 or greater. The IEL produces its best results in medium to high porosity formations drilled with fresh mud, or air drilled (dry) holes.

The induction device measures conductivity rather than resistivity. Conductivity and resistivity are mathematically related as follows:

$$C = \frac{1000}{R} \quad \text{or} \quad R = \frac{1000}{C}$$

Where: C is conductivity in millimhos/meter and R is resistivity in ohm-meters.

Since most people who work with logs are more familiar with resistivity measurements, the conductivity measurement of the induction tool is put through an electronic reciprocator and converted to a resistivity curve on the log. This along with the short normal and SP curves are then displayed. The most common format for displaying the IEL has recently changed so that the resistivity curves are recorded on a logarithmic scale.

Figure II-11 is a simplified depiction of an induction logging device. An oscillator supplies alternating current to the transmitter coil at D. This in turn creates an alternating field which creates current in a ground loop surrounding the well bore. This alternating current B then creates a field C around the imaginary ground loop which induces a voltage at the receiver coil E. The amount of voltage induced in the receiver coil is a function of the conductivity of the ground loop. If the formation material of which the ground loop is made has low conductivity, there will be less voltage induced in the receiver coil. The receiver response can then be calibrated to give conductivity figures for the formation through which the induction device is moved.

Electrodes A and M are used to record a 16 inch Normal Curve and an S.P. Curve at the same time the induction curve is being run.

Actual induction logging devices have more coils than depicted in order to more precisely focus the voltages that reach the receiver coils. A common configuration is one that has a total of six coils with a radius of investigation of 40 inches.

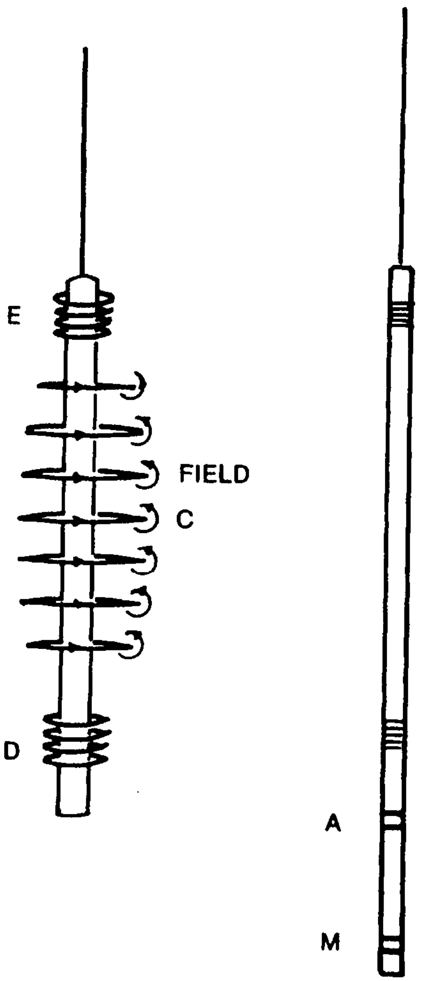
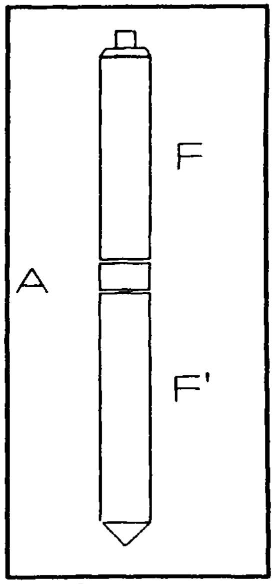


Figure II-11
Schematic-Induction Logging Device

3

GUARD RESISTIVITY LOG

The guard resistivity log was run as early as 1927 by Conrad Schlumberger. Abandoned for over twenty years, the log was then reintroduced by Birdwell. Reintroduction was necessitated by new drilling techniques utilizing salt-laden mud. These drilling muds greatly reduced the effectiveness of conventional resistivity logs, namely the Normal and Lateral logs. Today, the guard log is employed in all facets of geophysical logging from oil and gas to minerals and coal to water resource and environmental studies.



Guard Resistivity configuration
FIG III-1

Previously stated in this manual, resistivity is the measurement of electrical current flowing through rock strata saturated with formation fluids. Objectively, all downhole resistivity devices try to obtain a measurement that is insitu, independent of drilling fluids, borehole conditions and bed boundaries. Various devices have been engineered all with advantages and disadvantages. One device that has had success is the guard log.

In order to understand the guard log a brief overview of the Normal sonde is necessary. Figure II-6B illustrates the configuration of the Normal device. As seen, a constant current is applied to electrode "A" resulting in an electrical potential between "A" and ground "B". At radial points away from "A" equipotential spheres are established. These spheres are not only equal in potential but also are proportional to the resistivity of a given material that intersects these spheres. The Normal takes advantage of this by placing measuring electrodes ("M") at known distances from the current electrode "A". The greater "M" is from "A" the deeper the field of investigation. However, the further "M" is from "A" the poorer the resolution. The Normal is a give and take device, where distance is the condition of either sacrificing resolution or deeper, undisturbed readings.

potential. This is accomplished by using two guard electrodes (F,F') to focus the current electrode (A) into a flat disc with a thickness approximately equal to the length of the current electrode "A", while at the same time providing a radius of investigation approximately three times the length of one guard electrode. With a four inch current electrode and a three foot guard electrode, one could resolve beds down to four inches with an investigative radius of nine feet!

The guard electrodes (F,F') are automatically adjusted to the potential of the current electrode (A). When all three electrodes are at equal potential the magnitude of the current flowing from "A" is proportional to the resistivity of the formation being investigated. This configuration allows the sonde to have excellent thin bed resolution while minimizing borehole effects such as wash-outs and low Rm values (i.e., low mud resistivity, salt mud).

The application of the guard resistivity is extensive. The guard log, by virtue of excellent resolution and deep penetration, can be used in alluvium environments that are of mixed matrix with poorly defined bedding. In this environment the Normal log will often average the grading of a gravel zone that contains interbedded silts and sand. Whereas the guard sonde will delineate the grading, providing better detail on deposition. In well defined sequences of sand and clays the guard log can be used for well construction when accurate bed thickness is needed for placement of screen and seals (shoulder effect from adjacent beds are virtually nil). Wherever the normals are used an accompanying guard log is viable.

In the case of hard rock where fracture porosity is primary, the guard log will often index the fractures and provide information on whether the fracture is water bearing or not. The signature of fractures is unique in that when the sonde is across competent rock of no fracturing or filled fractures, the log will record 2000 ohm-meters reading (the rock matrix is without conductive fluids-porosity is essentially zero). When the sonde passes an open fracture with fluid the tool responds with reading less than 2000 ohm-meters. As fracturing increases or the fracture aperture becomes larger the lower the response of the reading. However, the log should never read less than Rw (the resistivity of formation water) unless the fracture is altered by clay deposits. The guard log has been corroborated successfully in these environments with the use of the Acoustic Borehole Televiewer.

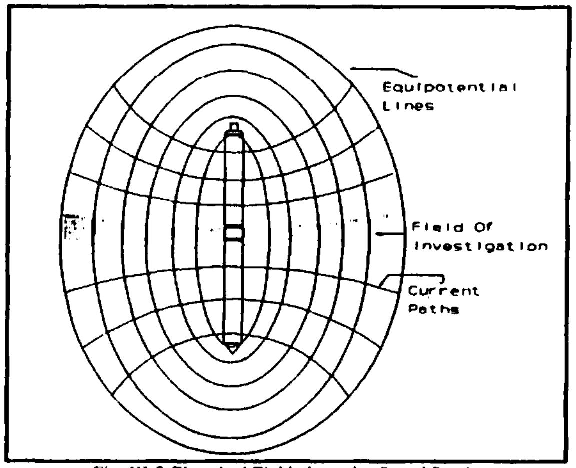


Fig. III-2 *Electrical Field about the Guard Sonde*

Because of the amount of metal used in the sonde's design a Spontaneous Potential curve is not provided. Instead a Gamma-Ray is used for correlation (the Gamma-Ray detector is located at the bottom of the sonde.) The measuring point

on the guard sonde is three feet above the bottom of the tool where the current electrode is located. The Gamma-Ray is approximately six inches from the bottom.

The units of measurements are in Ohm Meters for the Guard and API units for the Gamma- Ray. The log presentation is on API grid with the Guard resistivity in track 4 (if an E-log was run the guard is normally scaled the same as the E-log for correlation).

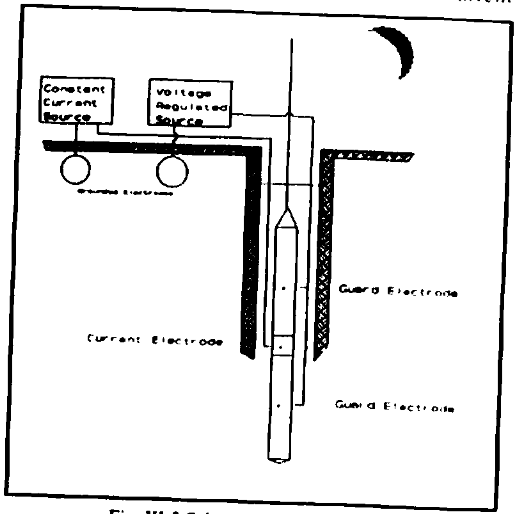


Fig. III-3 *Schematic of Guard Sonde*

4

NUCLEAR LOGGING

Nuclear logs are related to the measurement of fundamental particles or radiations from the nucleus of an atom. The most common logs are natural gamma ray, neutron and gamma-gamma or density logs. Nuclear logs may be run in a variety of downhole environments in either open holes or cased holes.

Since the radiation measured in nuclear logs is random in nature, minor fluctuations are present on all logs, and the logs will not repeat exactly. Repeat logging runs are a positive means of separating random changes from deflections related to lithology. Figure IV-1 shows a combination gamma ray-neutron tool that may be used to record either log separately or both logs simultaneously. Also shown is a density tool of the type commonly used in water and mineral exploration.

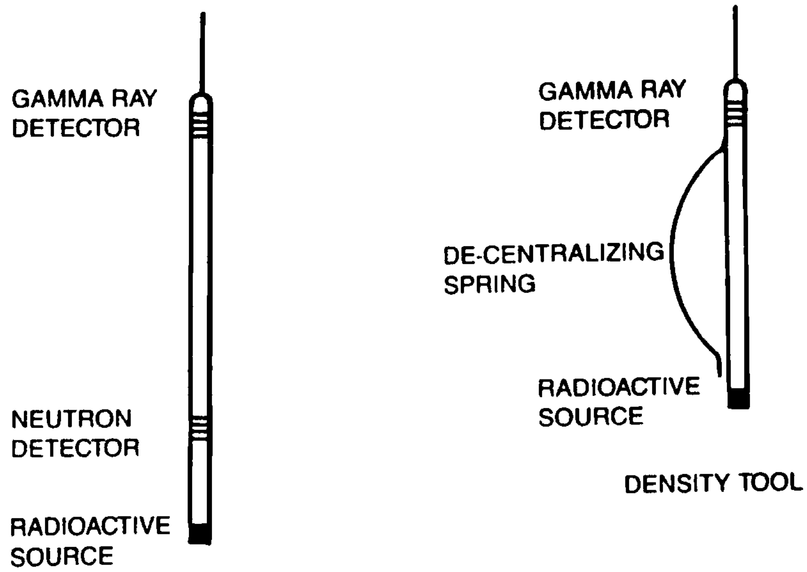


Figure IV-1
Schematic-Nuclear Logging Tools

Gamma Ray Log

Gamma ray logs measure the naturally occurring gamma emissions from the formation surrounding the borehole. These emissions are electromagnetic radiations that are released by a nuclei of an unstable element, decaying to a more stable state. In nature, the most significant of these elements occurring in abundance is potassium 40 (K40), uranium 238 (U238), uranium 235 (U235) and thorium 232 (TH232). The most plentiful of these elements is potassium 40.

As the unstable element decays, issuing electromagnetic radiation, the gamma ray probe detects the events by recording the number of particles or photon emissions. This detection is accomplished by use of a sodium iodide crystal optically coupled to a photomultiplier. As the incident photon enters the crystal a release of energy takes place in the form of illumination that is detected by the photomultiplier. A corresponding voltage is delivered to the surface where it is counted and averaged over a specific time period. Since radiation is of a statistical nature it is necessary to average the measurement of radiation over a selectable time period in order to derive a representative sample of the amount of radiation being emitted.

The greater the counting rate the more events the gamma detector is measuring, which in turn corresponds to the greater amount of an unstable element present in the formation. As mentioned, potassium 40 is by far the most abundant of these elements found in rock strata. K40 is found in all potassium bearing minerals such as potassium feldspars, biotite, orthoclase and several clay minerals rendering detection of these minerals via the gamma ray log. Consequently, as the content of these minerals increases within the rock strata the response of the gamma ray probe increases. Inversely, as the content of the clay minerals decreases the response of the gamma ray probe decreases. Gamma ray logs show decreasing strengths from shales and clays, to siltstones, to sandy siltstones, to clean sandstones and gravels.

Dependent on how clay is present within the quartz matrix, as dispersed particles, structural grains, or as laminations, both porosity and permeability of the rock will be affected. To arrive at accurate porosity readings one must know the fraction of clay volume to total rock volume.

Clay fraction = Clay volume/Total rock volume

The gamma ray log is often used to determine fraction of clay, when clay minerals contribute to a significant response on the log. An example mineral is illite. The formula for deriving clay fraction is:

Clay fraction = (GR - GRcl) / (GRs - GRcl)

Where: GR = the zone of interest
GRcl = clay bed
GRs = clean sand bed

A word of caution with regards to calibrating the log response, when the area of interest is near a clay bed, is the assumption that the area of interest contains the same clay minerals. While potassium and thorium are considered good clay indicators, uranium may be present in the rock strata that contains no clay, causing a false indication.

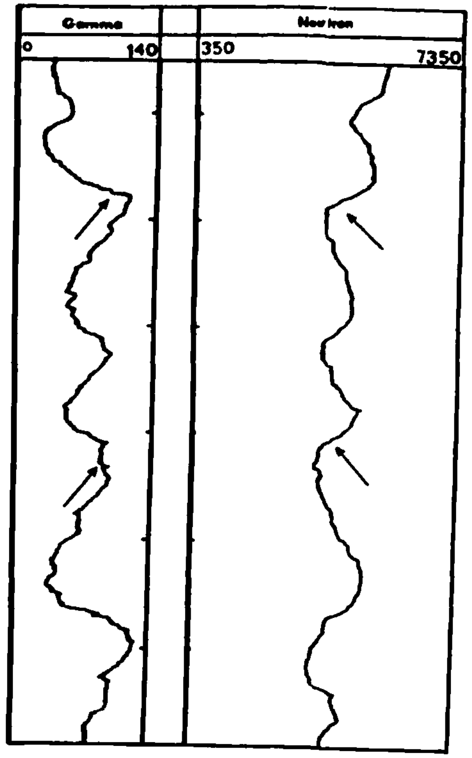


Figure IV-2
Gamma-Neutron Log Showing Upward Fining

When gamma active clays are present, a gamma ray log can be useful in revealing stratigraphic development. Figure IV-2 displays a sloping gamma response that is corresponding to changes in grain sizes. The fining trend is upwards. This log response can be revealing and easily identified.

When logging in metamorphic and igneous rocks of low porosity, the gamma ray response is dependent on the minerals within the rock. The one exception being along open, water bearing fractures where high gamma activity is recorded. This response is derived normally from either uranium becoming water soluble under acidic conditions, or the alteration of the host rock by water movement that has precipitated radioactive enriched minerals along the fracture wall.

Because the gamma ray log is a passive measurement of naturally occurring radioactive elements, and being lithologically dependent, it is an excellent correlation log. Gamma ray logs are normally run with all porosity tools and with an electric log when SP response lacks definition.

The vertical resolution of the gamma ray probe is a function of counting rate, time constant and logging speed. When all three are at optimum settings the vertical resolution is approximately one foot. Because of the

ATOMIC NO.	ELEMENT	CROSS SECTION IN BARNS CAPTURE	SCATTERING
1	Hydrogen	0.30	20.5
2	Helium	0.0	1.5
3	Lithium	64.0	2
4	Beryllium	0.009	6.1
5	Boron	7000	3
6	Carbon	0.0045	4.8
7	Nitrogen	1.75	10.0
8	Oxygen	0.0016	4.1
9	Fluorine	0.01	4.1
11	Sodium	0.5	3.5
12	Magnesium	0.4	3.6
13	Aluminum	0.23	1.5
14	Silicon	0.25	1.7
15	Phosphorous	0.31	10.0
16	Sulphur	0.53	1.5
17	Chlorine	33.0	10
18	Argon	0.62	1.9
19	Potassium	2.2	1.5
20	Calcium	0.43	9.5
22	Titanium	5.2	6.0
23	Vanadium	5	8
24	Chromium	3	4
25	Manganese	12.2	2.4
26	Iron	2.5	11.0
27	Cobalt	33.0	5.0
28	Nickel	4.4	18.0
29	Copper	4	8
30	Zinc	1.25	4.2
48	Cadmium	2500	5.3
50	Tin	0.69	5
51	Antimony	4.7	4.2
53	Iodine	6.8	3
56	Barium	1.25	8
74	Tungsten	16	5.7
78	Platinum	10.8	12
79	Gold	94.5	5
80	Mercury	425	15
82	Lead	0.2	13
83	Bismuth	0.02	9.2
90	Thorium	6	10
92	Uranium	2	8.2

Table IV-1
Cross Section for Neutron Capture and Scattering

statistical nature of radiation emission, repeatability of the log is not exact with respect to statistical variation of the counts. For this reason, the log will show repeatability in the shape of the curve but the individual curve peaks may be slightly different.

Since the energy of gamma emission is inversely proportional to distance, the greater the borehole diameter the less effective the gamma ray log response. Gamma ray logs can be run in gas filled holes of either open or cased wells.

Neutron Log

The neutron log, like the gamma ray, measures radioactive properties. Unlike the gamma ray, this log depends on the bombardment of the formation with neutrons from a source and measures secondary results brought on by this bombardment. As a comparison, the neutron log is like a resistivity log that measures the result of something being induced into the formation, while the gamma ray and SP logs measure naturally occurring phenomena.

The heart of a neutron logging tool is the radioactive source that emits epithermal neutrons. Characteristically, the source is made of Americium 241-Beryllium with a strength of from 3 to 5 Curies, which generate 2.2 x 10^6 neutrons per second per Curie. Americium 241 has a half life of 458.1 years and a specific activity of 3.24 Curies per gram.

Once a neutron is separated from the source, it begins its travel through matter. Since it is neutral, it will lose energy upon collision with the nuclei of other atoms. After a sufficient number of collisions with nuclei and the resulting loss of original kinetic energy, the neutron is slowed to a slow or thermal state. Although a formations ability to slow down neutrons is considerably affected by its hydrogen content, this process is usually not free from the influence of other elements. An atoms comparative slowing down power to neutrons, in terms of the number of collisions required to thermalize fast neutrons, will decrease with increasing atomic number in proportion to the ratio of the two atomic numbers, of the two atoms being compared. The capture cross section or probability that a neutron will interact with a nucleus depends upon neutron energy, size, mass and character of the atomic nuclei. Table IV-1 shows atomic numbers and capture cross sections for some common elements.

Two different types of logging systems are employed in the running of neutron logs. These are the neutron-gamma log and the neutron-neutron log. Early logging tools all used the neutron-gamma method of logging whereby the secondary gamma rays emitted during neutron capture were measured by a fairly insensitive gamma detector located a short distance from the source. The detector was kept small and insensitive so that it would react to little influence from the natural gamma radiation from the formation while responding to the wealth of secondary gamma rays. Most present day neutron logging tools are of the neutron-neutron type. This system uses a helium 3 detector about six inches long that responds to thermal neutrons as they pass through the detector, after being slowed by collisions with nuclei in the formation. This passage ionize detector gas

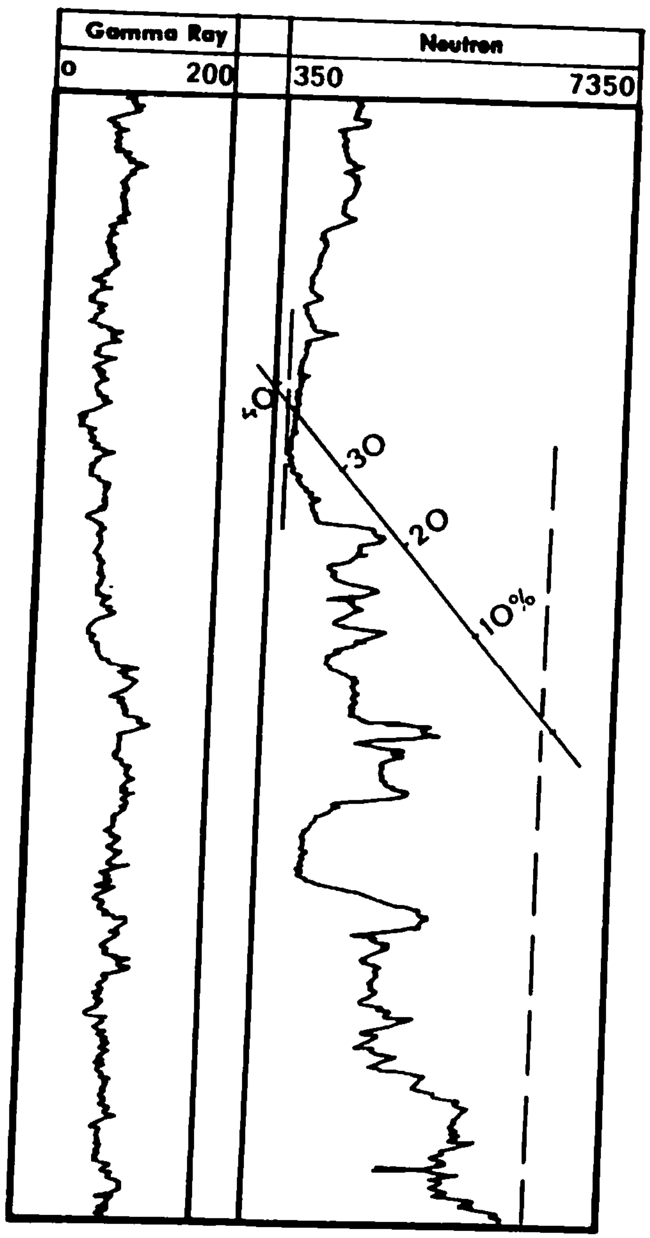


Figure IV-3
Porosity Estimating Using

and causes a pulse which is electronically processed within the tool and sent to the surface.

All quality logs are calibrated to standards set out by the American Petroleum Institute and are recorded in API Neutron Units. Calibration is accomplished by placing the tool, while attached to the logging cable, into an environmental calibrator that duplicates the conditions and porosity of the API test pit at the University of Houston.

The prime advantage of the neutron log lies in the fact that it is a reliable indicator of porosity of reservoir rocks. It has been proven that the response of the neutron curve is empirically related to the hydrogen content of rocks and that the hydrogen content of liquids in pore spaces can be accurately related to porosity in most cases. Figure IV-3 has a neutron log in the right hand tract that has a porosity scale superimposed on it. Rock samples taken while drilling tend to confirm the reliability of the plotted scale.

Density Log

The density log represents the electron density of the formation. By virtue of this, porosity can be determined along with lithologic identification, gas detection and clay fraction when used in conjunction with other porosity tools.

The density probe design is similar to the gamma ray probe in that the downhole circuitry is accompanied with a detector. In the case of a compensated density probe there are two detectors. This detector, with the use of a backup arm or spring, is pushed against the borehole wall. A radioactive source, located some distance and on the same plane as the detector, bombards the formation with intermediate gamma ray energies. The phenomena of Compton scattering takes place in which back scattered gamma rays are received by the detector, or detectors.

Compton scattering is the elastic collision of gamma rays with orbiting electrons. Upon collision the gamma ray and electron change both direction and velocity. Compton scattered gamma rays are therefore proportional to electron density of the formation. Electron density is closely related to bulk density since true density is the mass number. A. which is the total number of neutrons and protons within the atom. With Z being the atomic number, a ratio of Z/A equal to 0.5 is acceptable in calculating true density when an electron density is known. In most water bearing geology, this ratio is constant.

As mentioned, density logs are often used to derive a formation porosity, P, defined as the ratio of pore volume to total volume of rock. Within intergranular rocks, porosity is the void space between grains, intragranular porosity is the void space within the grains, and vugular or fracture porosity is often considered secondary porosity. Density derived porosity is calculated from measured bulk density.

p = pma (l-P) + pfl x P

or, PD = (pma-p) / (pma-pfl)

where,

PD = density derived porosity

pma = density of matrix

Within a given matrix value, as the p of the equation changes there is a corresponding change in the porosity. Often a matrix value is assumed for a single mineral and if that value changes within the formation, an erroneous porosity will be given. A formation may contain more than a single mineral, necessitating caution in choosing a matrix, or obtaining a core derived density matrix. For example, if the matrix value was assumed to be 2.65 gm/cc and the log derived density was 2.50 gm/cc, the porosity would be given as 9.09 percent. If the actual matrix value was 2.60 gm/cc then the porosity would be 6.25 percent, a difference of 2.84 percent.

Density log response is also used for mineral identification when run with other porosity devices. Each porosity device responds to a particular mineral in quite different ways. which when cross-plotted can often identify the mineral. If only one porosity device is used, however, then it is extremely important to cross-correlate that log response to the other available logs. For instance, a density log run alone might often be unclear in distinguishing shale or clay, from sandstones since both rock types have similar densities. The use of a gamma ray log should help in the definition. Like the neutron log, the density logs basically see total porosity, where a false porosity would be derived if the rock were vugular. If a sonic log is available, the porosity can be corrected since sonic energy is thought to avoid the vugs and fractures, by traveling through the matrix instead, the path of least resistance.

The density probe can be run in either water or air filled holes. By virtue of being a sidewall contact probe, the density tool is considered to have good vertical resolution. Vertical resolution is a function of the source to detector spacing, the time constant for averaging the counts and the line speed. If an appropriate time constant and line speed are maintained, the vertical resolution is equal to approximately half the distance between source and detector.

The compensated density probe, employed by most service companies, consists of two detectors located on the same plane as the radioactive source. As the name implies, compensated density probes are designed to reconcile inaccurate densities due to borehole conditions. As the density probe rides the borehole wall it is influenced by the condition of that wall. In a rugose hole the single detector, if not entirely pushed against the borehole wall, will average the densities of either the air or borehole fluid with that of the formation. False densities can also be logged due to heavy mudcake. The compensated density probe employs two detectors, one near the radioactive source which is influenced by mudcake and tool standoff, and a far detector which is mainly influenced by the formation. The counting rates of both detectors are plotted against each other for known densities at zero gap, and then for fluid densities greater than formation density, and fluid densities less than formation density. Essentially, the compensated density probe is designed to eliminate borehole conditions to derive actual formation densities.

5

CALIPER LOGGING

Although they are not regularly run on water wells, caliper logs have many useful applications in both open and cased holes.

Caliper logs measure the average diameter of drilled holes by the use of two or more arms which are mechanically linked to a precision potentiometer that biases an electronic circuit within the tool body. Changes in hole diameter are converted to pulses that are transmitted to the surface for recording. Logs are usually presented as a single trace that displays the average hole diameter in inches.

When run with an electric or nuclear log, the caliper is very useful as an interpretive aid in substantiating the differences in log readouts that result from hole diameter effects rather than from lithologic changes. Most logs that respond to lithology are also affected by changes in hole diameter. On all charts used for log interpretation, hole size must be known in order to arrive at proper quantitative values.

A caliper log can be used to determine quite accurately the proper amount of gravel needed to fill the annular space between the casing and the borehole wall. Figure V-1 is the log of a well in which a great deal of formation washout was experienced during the reverse drilling of a 28 inch hole, until at a depth of 600 feet it was deemed necessary to add mud in order to stabilize the hole. With the exception of a 30 foot zone below 900 feet, the hole remained fairly true to gauge for the balance of the drilling, even showing some undersize hole where mud cake built up across some permeable zones. Calculations of the gravel required to fill the annular space showed that an excess of 20% more gravel would be required to fill the annulus than would be expected without benefit of the log. A caliper log is also essential for selecting seats for straddle or isolation packers. Packers have an effective range of hole diameters beyond which they will not set or will fail when inflated.

Calipers in cased holes are used to determine casing diameters where remedial work must be performed on the well. For various reasons, records of casing diameters and other information about existing water wells may be difficult to find. When video inspection of a well indicates that remedial work is necessary, and the work to be performed, such as casing repair, depends on a knowledge of the exact well diameters, then the caliper becomes a valuable device.

Figure V-2 is the caliper log of a well that was thoug[illegible] contain two different sizes of casing. The caliper clearly indicates that [illegible]ird diameter was either placed when the well was drilled, or put in at a later date during a repair job. The caliper log confirms a visual inspection made previously of badly damaged casing just below 200 feet and a breached hole at 215 feet in 14 inch casing that is the result of a compression failure.

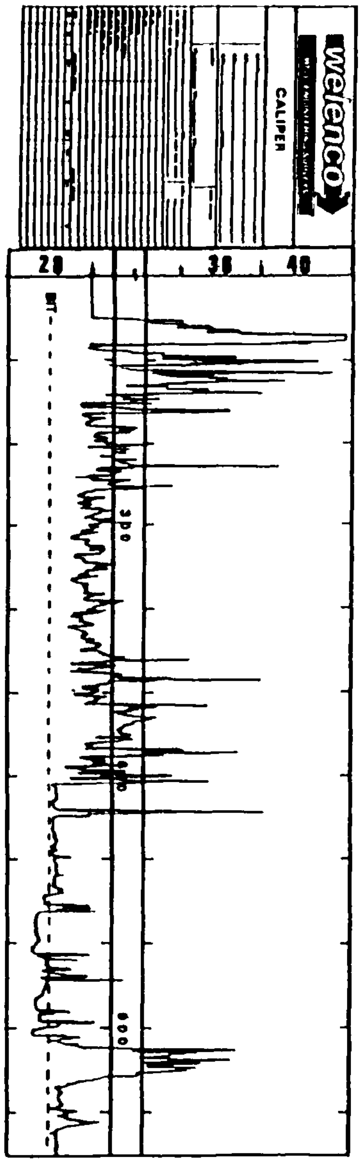


Figure V-1

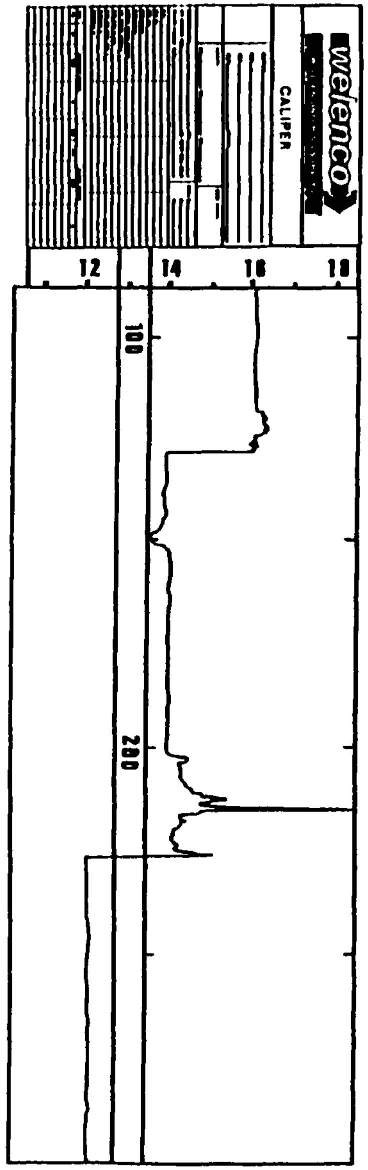


Figure V-2

6

SONIC LOGGING

The sonic tool is designed to measure the time it takes for a pulsed compressional sound wave to travel one foot, or *interval transit time*. The interval transit time for a formation depends on the elastic properties of the formation which are related to lithology and porosity. In general, waves travel faster through denser formations. Therefore, an increasing travel time for a given type of material indicates increased porosity.

The speed of sound is usually measured by how far the sound travels in one second. Travel time (Δt) which is the measurement used in sonic logging, is taken as the time it takes for sound to travel one foot, with the time being measured in millionths of a second or *micro seconds*. One measurement is simply the inverse of the other. For example, the velocity of sound in air is 1088 feet per second. Its travel time is computed as follows:

$$t\ air = \frac{10^6}{V} = \frac{1{,}000{,}000}{1088} = 919 \text{ Microsec per foot}$$

MATERIAL	SONIC VELOCITY, V FT/SEC	TRAVEL TIME, t (= 10⁶/V IN MICROSEC)
Oil	4300	232
Water (mud)	5000-5300	189
Shales	6000-16000	167-62.5
Sandstones	up to 18000	55.6
Limestones	21,000	47.6
Dolomite	23,000	43.5

Table V-1
Travel Times for Common Materials

The Wyllie equation was developed to relate sonic travel time to formation porosity much the same as density is related to porosity. The equation is written:

$$\emptyset = (\Delta t - \Delta tma)/(\Delta tf - \Delta tma)$$

Where: t = Formation travel time from log
t_{ma} = matrix travel time
t_f = fluid travel time

In its simplest form, a sonic tool would consist of a transmitter emitting ten to thirty bursts per second sound pulses at a frequency of about 23,000 Hertz and a receiver located at a distance of several feet to time the arrival of these bursts. The difference in time from transmission to reception is the time that it takes each pulse to travel latterally through the drilling fluid to the bore hole wall, through the rock formation and back across the drilling fluid to the receiver. This difference is presented on a log as an analog curve that is scaled in micro-seconds, usually 50 to 150 for ten scale divisions on the log. One can see that, with the short tool spacings and very fast travel times involved, variations in hole diameter and tool centralization in the borehole could result in unexplained differences in travel time for the same density rock. These differences are essentially all canceled out by the use of *borehole compensated sonic* devices where compensation for hole size differences is provided by placing two alternately pulsed sonic transmitters above and below two sonic receivers and centralizing the tool in the borehole. Figure V-1 shows the relative location of the two pulsed transmiters and two receivers. Electronic circuitry continually solves the equation:

$$T = \frac{(T3 + T4) - (T1 + T2)}{4}$$

In addition to the analog curve, some service companies offer a variable density log, or VDL, which is photographed by a camera that is attached to an oscilloscope. Figure V-2 illustrates the conversion of a standard x-y wave form as it would appear on a scope to the VDL presentation. The lower picture is the x-y scope picture of a 4 foot single receiver signal with time increasing to the right, 200 - 1200 microseconds, and amplitude increasing positively above and negatively below zero amplitude. Above this is preparation of the acoustic signal for the VDL log. All positive half cycles appear and will be recorded as dark streaks and all negative half cycles, which have been cut off, will appear as light streaks. Zero amplitude will appear gray. Next is the VDL with the logging tool stationary. The top picture represents film and tool movement coordinated on a 5 inch = 100 foot de[illegible]cale.

Figure [illegible]-3 illustrates a variable density log of a well which was logged [illegible]

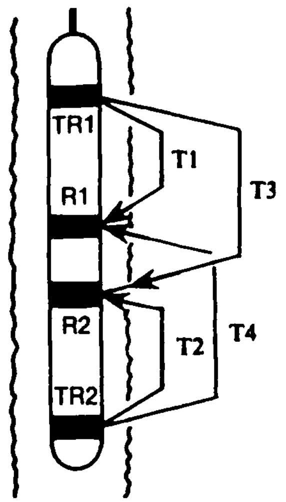


Figure VI-1
Schematic Borehole Compensated Sonic Device

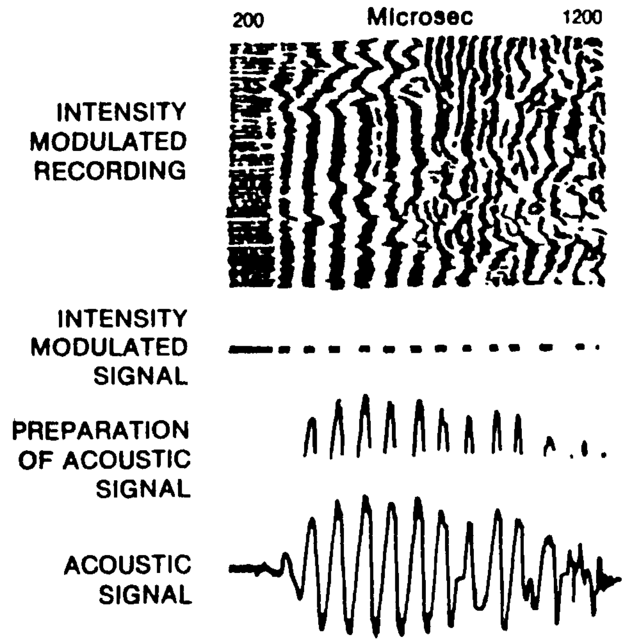


Figure VI-2
Sonic Presentation Technique

would have been adversely affected by being run through casing, the VDL clearly shows that a reasonable correlation can be established between the two logs. Although the VDL is used primarily with sonic cement bond logs, it has proven very useful in locating fractures in hard rock areas.

Cement Bond Log (CBL)

With the increasing demand for water wells to be sealed from contaminated surface runoff water, the sonic log presentations have become quite useful and reliable. A cement bond log presents information as to the quality and volume of cement, which has been placed in the annular space between a wells' casing and the wall of the borehole.

During the CBL logging process, the casing must be full of fluid which is used to transport tool signals to and from the casing. The process is carried out and a log compiled of the ability of the cement grout to absorb or transport a sonic signal. This signal is proportional to the quality or hardness of the cement and in most cases will show the quality of bonding of the cement to the outside of the casing, and to the wall of the wellbore. If a log shows good quality in this sheath and its bonding, over any considerable distance or length of well, the well can be considered effectively sealed.

A CBL indicating poor seal quality, may actually show casing collars as points where sonic signals are transmitted differently than other areas of the same joint of casing. This is simply the result of cement not effectively in contact with the casing, allowing two mediums to pass sonic signals at different speeds. This fact is evident when a CBL log is used to show improvement of cement quality over a number of days after placement, since compressive strengths of most cementing materials will continue to improve with time. The problem of cement not bonding to the casing or the wellbore usually will not improve on a particular well. The CBL log may also show poor quality, relative to the cement strength, of an unconsolidated wellbore material or very soft formation with which the cement grout is in contact.

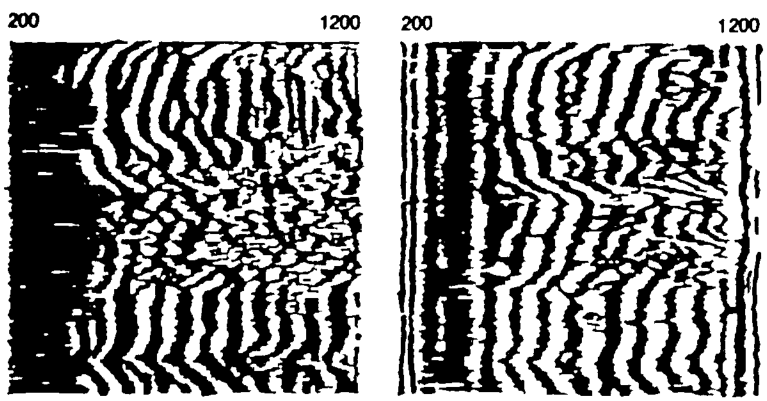


Figure VI-3

Variable Density Logs

7

DIRECTIONAL SURVEY

A continuous directional survey is sometimes run on water wells in order to determine how straight and how vertical the hole is. Depending on the detail desired, the survey may be set to take readings from every ten to every one hundred feet of hole depth. The survey indicates the depth of the reading, the borehole inclination at that depth and the direction of the inclination. At the end of a survey, a computer is used to calculate and present the true vertical depth to bottom at total depth and the horizontal distance and direction to the hole bottom from a point centered directly under the surface location.

Figure VII-1 is a printout of a survey performed on a core hole used for mineral prospecting. In everyday drilling and construction of water wells, it is common for the bottom of the hole at total depths of 1,000 feet to be within 5 feet or less, of a vertical line drawn through the center of the surface location.

BEARING	300.23
CLOSURE	32.39
TRUE VERTICAL DEPTH	289.31

FOOTAGE	INCLINATION	DIRECTION
0292	12.0	339
0290	12.3	337
0280	11.9	334
0270	11.4	329
0260	11.0	322
0250	10.9	317
0240	10.6	316
0230	10.3	313
0220	09.9	307
0210	09.5	304
0200	09.1	302
0190	08.6	300
0180	08.3	299
0170	08.0	295
0160	07.6	290
0150	07.1	286
0140	06.7	282
0130	06.3	280
0120	06.0	277
0110	06.2	270
0100	05.4	266
0090	04.6	270
0080	04.3	264
0070	04.0	261
0060	03.7	256
0050	03.6	252
0040	02.8	246
0030	01.8	245
0020	01.2	242
0010	00.4	248
0000	00.0	099

Figure VII-1
Example Directional Survey
Data Printout

8

PRODUCTION LOGGING

After drilling, completing and producing a well, additional logs or surveys are valuable in helping to evaluate the mechanical condition, existing problem or approaching problems associated with the producing life of the well. During the drilling phase of a well electric logs are used to help define the lighology and other physical aspects of the strata which have been penetrated by the drill. After running steel or plastic casing in the well, those logging devices requiring electric current to be transmitted through the aquifer are eliminated from further use.

Wells which have casing in place can be examined, but with different logging devices and usually for entirely different reasons. These logs examine and record the physical aspects of information which can be transmitted through the casing, such as natural gamma radiation and temperature. Sonic devices actually examine parameters outside the cased well by emitting mechanical energy and observing the transmitted results.

Perforations in the well casing may allow fluids to enter, which can be observed for salinity by logging devices. These fluids may be physically retrieved and examined for all chemical constituents, using a depth specific sampler. Sampling capability is especially important where waters have been detected moving from one area of perforated casing to another area. These interzonal flows are not evident at the surface during normal operation of the well and can only be defined and the flowrates measured, by devices lowered into the well. Flowmetering surveys can measure extremely slow flowrates and flow directions.

The mechanical condition of a well can be viewed in real time with presentations made by a television camera lowered into the well. The video signal is recorded on a cassette for reviewing at the office and provides a perfect reference in the future for a comparison of casing conditions versus time. Video is a perfect tool for updating undocumented completion methods, depths and areas of perforated or screened casing.

Section One

TEMPERATURE LOGGING

Temperature logging provides a means for the continuous measurement and recording of borehole temperatures versus well depth. Most temperature logging tools utilize high resistance semi-conductor sensing elements, which are quite small in mass. They can rapidly respond to increases in temperature with proportionately large reductions in electrical resistance. Such changes cause an imbalance in an electrical circuit which can be formed into pulses and recorded as degrees of temperature. Small sensor size makes for a short response time and permits their use in small diameter probes. The sensing element is located on the very bottom of the tool, so that during a logging run into the hole the element encounters the existing borehole temperature in an undisturbed state. Logging into the well also eliminates temperature influences from the mass of the tool. The left hand curve in Figure VIII-1 is an absolute temperature log recorded in an area with a geothermal gradient of about four degrees per 100 feet of depth. Generally, gradients run from one and a half to three degrees per 100 feet.

Temperature logging is used to determine liquid levels, cement tops, fluid entries, injection and production profiles and zones of lost circulation encountered during drilling. In the quantitative interpretation of electric logs an accurate knowledge of formation temperature is a must. Temperature logs may be run in cased or uncased wells and in any type of fluid.

The differential temperature log continuously compares, via a time delay system, two temperature measurements made by a single sensing element. It provides a means of measuring minute temperature anomilies. This enables the graphic and emphatic display of relatively small changes in temperature which may not appear significant on the gradient log. It should be understood that a *differential* temperature curve contains no new information, it is simply the data from the gradient curve presented in a different form. As the name implies, the differential curve is a record of the rate of change of the gradient curve and can be recorded at a wide range of sensitivity.

Figure VIII-2 is an idealized presentation that illustrates the differential temperature principle. Each time there is a change in the slope of the gradient curve, the differential exhibits a corresponding offset. The right hand curve of Figure VII-1 is a differential curve made at the same time that the gradient curve was logged. Notice that a very small change in the gradient curve shows up as a relatively large excursion on the differential. These changes are probably caused by the flow of waters in sands outside the casing.

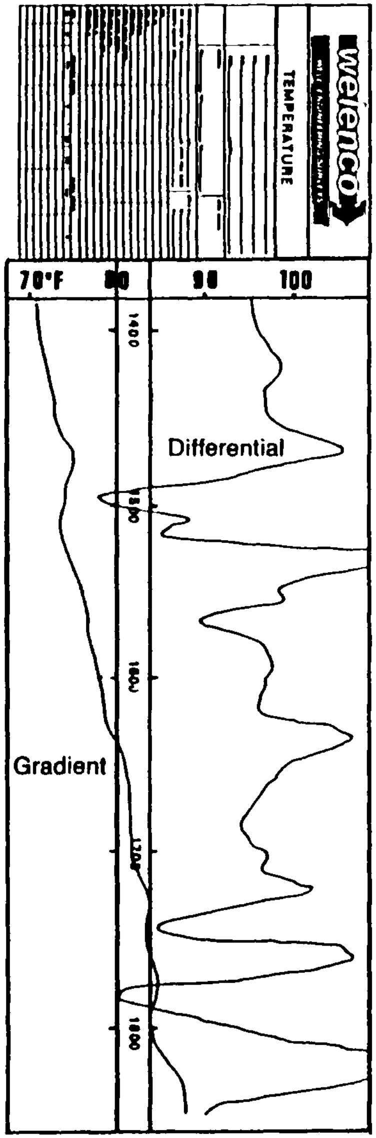


Figure VIII-1
Temperature Log Showing
Gradient and Differential Temperatures

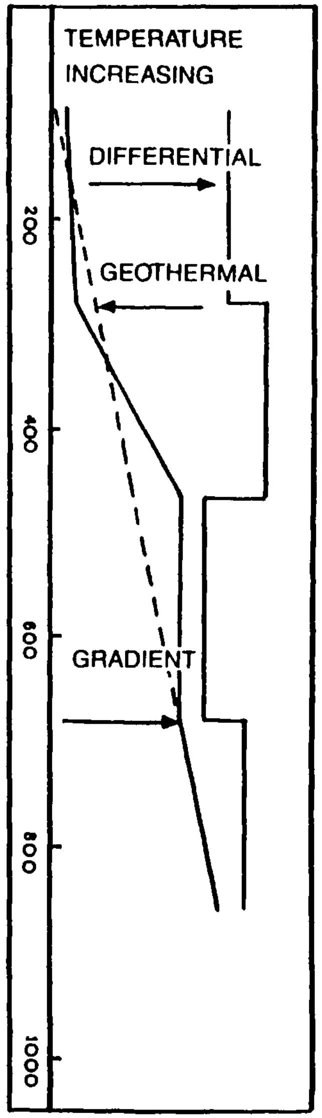


Figure VIII-2
Gradient and Differential
Temperature Presentation Technique

Section Two

RESISTIVITY LOGGING

Resistivity surveys are used to measure water resistivity within cased or uncased wells under both pumping and non-pumping conditions. The differential resistivity tool measures and presents not only the resistivity gradient of the wellbore water, but also detects minute changes in water resistivity by the use of a differential circuit which makes time delayed resistivity comparisons. The method of presentation is identical to that used for temperature and differential temperature logging.

The device is actually presenting a measurement of the total dissolved solids (TDS) in the wellbore water. This type of measurement is especially important in a non-pumping well as it may be possible to detect the layering effect of different waters across the welbore. In a pumping situation, TDS changes quite often correlate with actual entries of water. The differential resistivity feature of this device makes very visible presentations of small resistivity anomilies.

As with the differential temperature log, it is important to maintain a constant logging speed when running the resistivity survey. A speed of thirty feet per minute usually gives excellent results.

The type of interpretation available from this log is qualitative. Figure VIII-3 is the log of a well which has perforations from 100 feet to the bottom at 250 feet. The pump had been removed from the well and a flowmeter log indicated movement between aquifers starting at 104 feet, moving downward and gaining additional water entries all the way to 180 feet, with major entries at 134, 146, 150 and 170 to 180 feet. The major exit area was from 230 to 240 feet with some water exiting out the bottom of the well. It is possible to detect varying water qualities at the points of entry. In this case, the well contains fresher water above the top perforations, while water with the highest TDS concentration is entering through the top perforations. Quality gradually improves to the lowermost entry at 180 feet, from which point downward the quality remains constant.

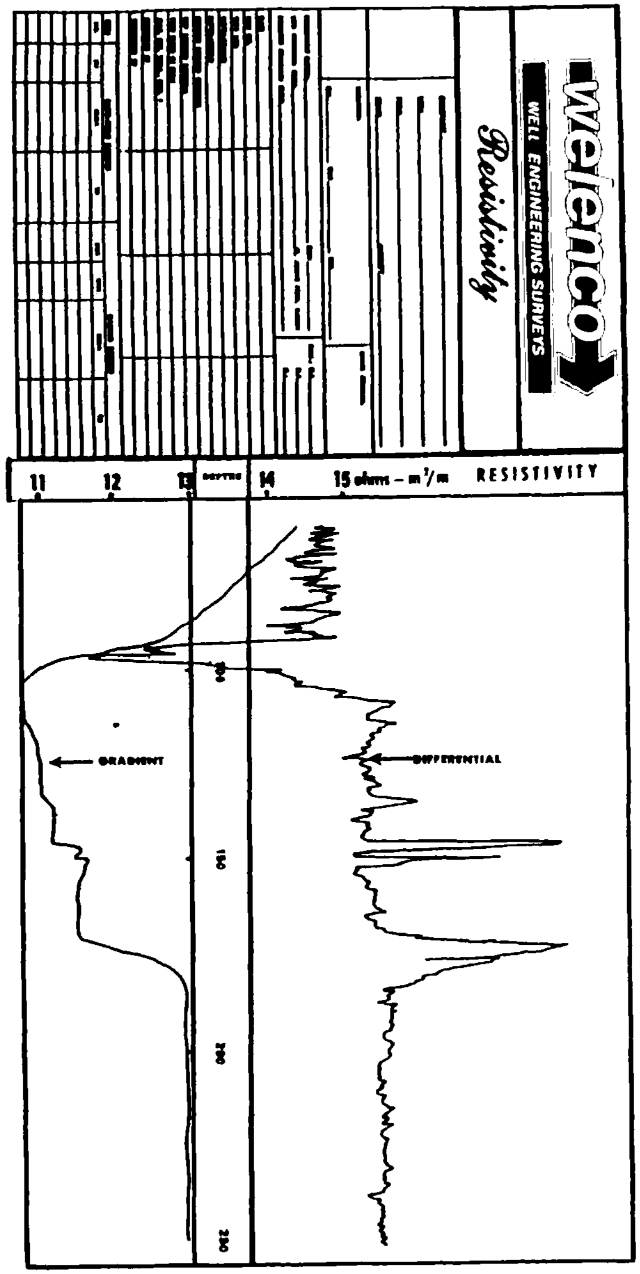


Figure VIII-3
Fluid Resistivity Log
Showing Gradient and Differential
Fluid Resistivities

Section Three

VIDEO SURVEY

The reconfiguration of a conventional television camera has become a standard tool for the surveying of water wells. A picture can be worth more than ten thousand words, by showing the actual mechanical condition of well casings, perforations, failure areas, tuberculation accumulations, casing depths and water entries.

The video is displayed in the logging truck while the camera is being lowered into the well, showing a black and white, or color picture. The picture is viewed by the camera lens focused vertically downward to an area approximately two feet deeper where a light is located. Quality pictures are obtained usually after a 48 hour quieting period has elapsed since water disturbance occurred. A video cassette is made for future reference, showing the camera depths superimposed in the center of the picture.

Older wells may not have been documented by a driller, requiring the simple video survey to determine effective depths, casing depths, and the location, methods and apparent effectiveness of casing perforations.

Tuberculation buildup which covers perforations almost always indicates water entries are being seriously restricted. This information may be beneficial in re-confirming aquifer capability, if the well can be restored to its original production rate. The use of explosive/implosive stimulation systems may remove restrictions in the perforations and the gravel pack areas behind the casing.

Open hole video surveys have been used in hard rock wells to view water producing fractures which intersect the wellbore. Fracture angles of incidence greater than approximately 45 degrees, generally do not appear on a conventional sonic log in open or cased hole.

Section Four

FLOWMETER SURVEY

Flowmeter surveys are used to measure fluid flow rates within either cased or uncased wells. They determine production rates from all zones to the well, provide injection and production profiles and locate holes in the casing. The spinner type flowmeter measures the movement of water by the use of a low inertia impeller which spins on precision carbide bearings. A small perforated disc connected to the end of the impeller shaft activates a magnetorestrictive counter in the body of the tool. As the impeller and the disc turn, these perforations cause a magnetic field fluctuation which is electronically converted to pulses and transmitted to the surface recording system for further processing. Since the WELENCO flowmeter sends twelve pulses for every revolution of the impeller, then the counts per second (CPS) must be divided by twelve to determine revolutions per second (RPS) of the impeller. Although the relationship between water flow and impeller speed can be expressed either by counts or revolutions, all WELENCO logs and charts are scaled in counts per second.

Flowmeters are sometimes run on water wells that are not being pumped, to determine if water movement between aquifers of different hydraulic heads is taking place. At times, the flow is insufficient to initiate impeller rotation while the flowmeter is stationary within the well. However, continuous surveys run up and down hole at identical speeds can yield valuable information, such as which direction the water flow may be moving. If the water is moving downward, then the up run will show a higher count over the interval where the water is moving. Conversely, if the water is moving up then the down run will show a higher count rate. Up and down continuous runs in a wellbore that has no water movement will have identical counting rates if cable speeds are maintained evenly. Interzonal flows are of special interest when studies are being made of contaminated wells.

Under dynamic conditions where a submersible pump has been installed and the well is being pumped, a flowmeter survey can be made which will log the different flow contributions of each water entry. If the well will respond with sufficient production rates, the pump intake should be located above the uppermost casing perforation. An access pipe is required for lowering the spinner tool into the well and should extend preferably to a few feet below the lowermost point of the pump intake. When pumping has become stabilized, the spinner flowmeter is lowered to a position in the casing below the access pipe but above the uppermost perforations. At this level, a one or two minute measurement or *stop check* is made with the tool stationary and all of the produced water passing it. This establishes 100 percent spinner response and measures the total gallonage being produced. These stop checks are then made at regular intervals either to the bottom of the well or until flow is so low that the impeller is no longer energized. The counts per second which are recorded during these stop checks can be plotted versus depth to show a profile of the water entries.

After stop check recording, it is recommended that several continuous downward logs be made against the upward water flow, at different cable speeds. Cable speeds of 40, 60 and 80 feet per minute should give a profile of the production and confirm the stop check results. An added advantage is to produce a profile near the well bottom where the impeller had ceased to rotate while performing the stop checks. By using the calibration chart of Figure VIII-4 and the continuous log, a true zero flow depth can be determined. Figure VIII-5 shows that zero flow in this example is never obtained, as water is being produced from the very bottom of the well.

A modified flowmeter with an attached funnel can facilitate stop check logging under non pumping conditions. This funnel deflects the flow into

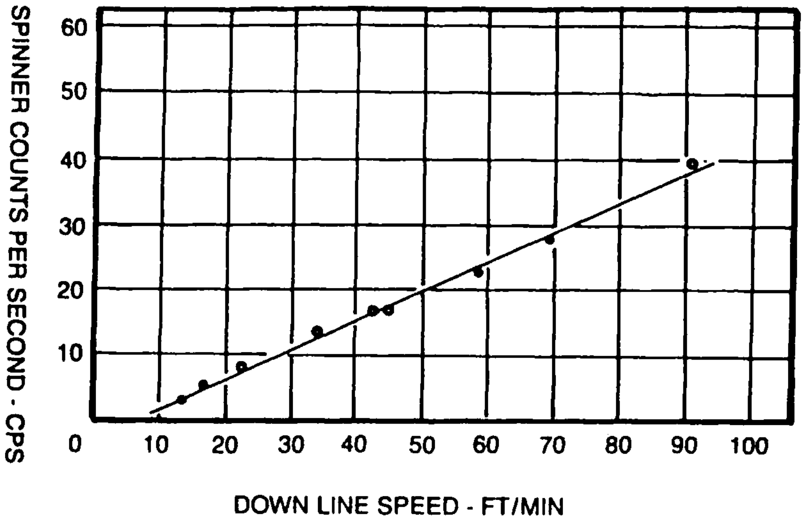


Figure VIII-4
Spinner Response Chart
CPS versus Line Speed

and around the impeller. This flowmeter is presently being researched and developed, and appears to have excellent low flow rate measurement capabilities. Its repeatability makes it an exceptional device for pinpointing water entries and exits from a well casing.

A spinner flowmeter which incorporates a folding metal petal basket deflector that may be opened and closed at will, has been utilized in small diameter wells and will measure relatively low flow rates. This device will be adapted to the larger casing diameters usually found in the water industry.

Section Five

BRINE TRACER SURVEY

In efforts to measure vertical water movements inside larger diameter wells, the spinner flowmeter may give unacceptable results, especially at very low flowrates. A tracer method measures flowrates by ejecting a small amount of liquid into the flowstream, then detecting the trace at a later time. By [illegible]ing the trace travel time, the distance traveled and knowing the inside di[illegible]ter of the well, flow rates are easily calculated. Since it is not

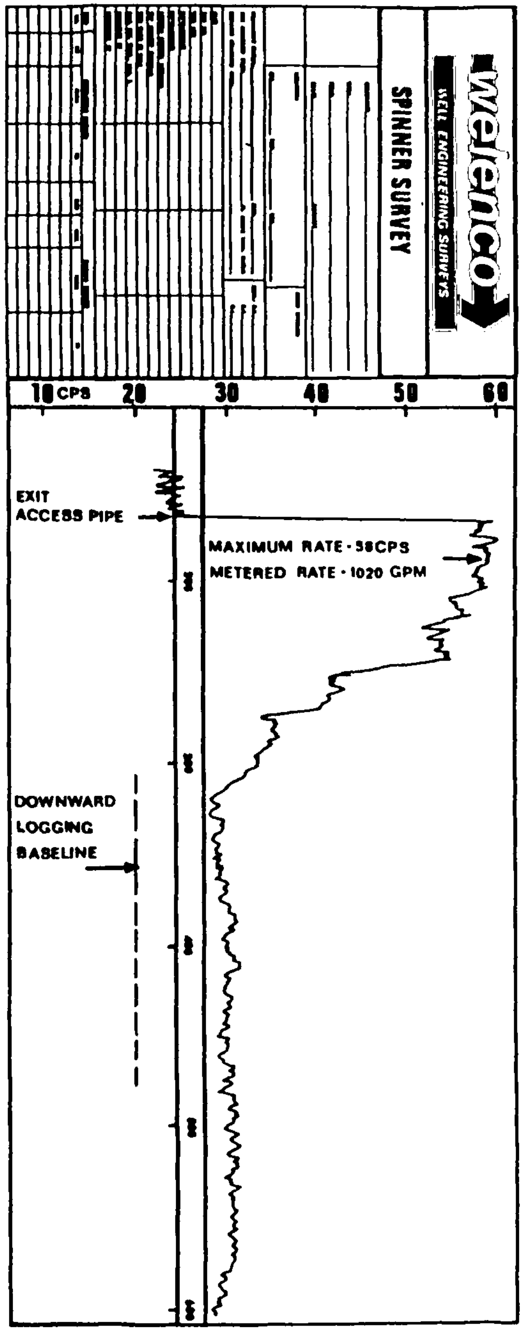


Figure VIII-5
Spinner Flowmeter Log
Spinner Counts versus Depth

permissible to use radioactive tracer liquids in potable water wells, the brine tracer tool uses salt water as the tracer material. Whereas the radioactive tracer was sensed with a gamma ray detector, the brine tracer is sensed with an electrical conductivity probe. Figure VIII-6 depicts the brine tool configured for tracing downward water movements. In this case, the detection electrodes are located a fixed distance below the ejection ports. While logging wells where upward flows are to be detected and measured, a brine trace is ejected, then the tool pulled upwards after a short waiting period. When the detector passes through and logs the brine, the exact elapsed time is logged. Having measured the distance between brine ejection and detection depths, flow calculations are accurately made.

Because the brine has a density greater than that of fresh water, it slips downward in a column of fresh water and will cause an error if not allowed for. A correction for slippage is applied in order to accurately determine the rate of water movement.

Ejector tool stops are usually made at regular intervals throughout the perforated intervals of a well. A plot of the travel times versus depth looks very much like a spinner flowmeter stop check log and will indicate where velocities change as the result of waters entering or leaving the well through some type of casing perforation.

The following calculations are made to determine water flowrates inside a well, using the brine tracer survey results.

Flowrate G, in GPM = 0.25974 x A x V

Where:

A = Area = 3.14/4 x ($Dcsg^2$ - $Dtool^2$)

V = travel distance, inches / travel time, seconds

Dcsg = diameter of casing, inches

Dtool = diameter of tool, inches

48 inch = travel distance

0.25974 = conversion factor

For flow calculations using a 48 inch tracer travel distance and a tool diameter of 3 inches, downward flow calculations can be reduced to the following for the various sizes of casing:

For 14 inch casing,
G = 1830.17 / tracer travel time, seconds
For 16 inch casing,
G = 2417.39 / tracer travel time, seconds
For 20 inch casing,
G = 3826.72 / tracer travel time, seconds

As an example, where a 3 inch tool with 48 inch travel distance is being used inside 20 inch casing, refer to Figure VIII-7. The logged time from eject point to inflection point of tool response is 6 chart divisions. Since each division is equal to 6 seconds, the total tracer travel time is 36 seconds.

G = 3826.72 / 36 seconds, or 106.3 GPM

This does not allow for slippage of brine tracer in fresh water, which has been determined to be 100 seconds per 48 inches. For all flow calculations for this well, apply a correction factor of:

G = 3826.72 / 100 seconds, or 38.27 GPM

A final correct solution becomes 106.3 - 38.27, or 68.03 GPM

Figure VIII-6
Brine Tracer Survey Tool

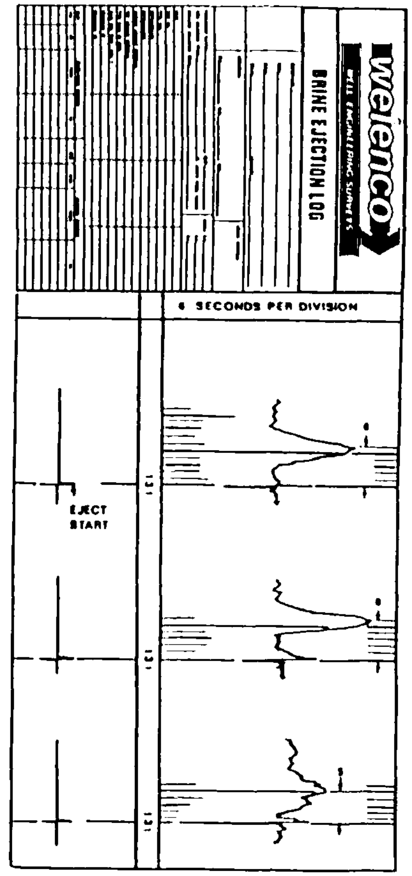


Figure VIII-7
Brine Ejector Stop Check Log

Section Six

DEPTH SPECIFIC SAMPLING

Over the years, the methods for sampling groundwater have varied from catching surface samples to different types of fluid bailers. Since these methods have many drawbacks, the WELENCO depth specific sampling devices were designed to secure and retain high quality samples from any descrete depth in a well. This type of sampling has many advantages, the most important being to obtain a representative sample of an entry from a particular aquifer, with minimal mixing of other waters.

The enforcement of water quality regulations has increased the need for monitoring of water production, especially where well abandonment may be required due to groundwater contamination. The studies of contaminated groundwater aquifers and the methods for alleviation, require sample analysis of constituents found, in parts per trillion.

Sampler operation begins with a complete disassembly, cleaning and sterilization of all components which may come in contact with the liquid being sampled. The analyzing laboratory may require certain sterilizing fluids and passivating methods, depending upon the contaminant being researched. After reassembly, the sampler may require purging with a liquid or inert gas such as nitrogen. Laboratories have required purge samples be analyzed for a baseline of any latent contaminant. The final step before running to sample depth is to evacuate and seal the sample chamber.

The electric logging cable is used to lower the sampler to the required depth, where it is actuated by power from the logging truck. A motor operated valve is cycled open, then closed, allowing the water sample to replace the vacuum inside the sample chamber. For security, the valve can be actuated only by electric power supplied from the surface.

After surface retrieval, and sampler integrity checked, the sampler is tapped into laboratory glassware for later analysis. If desired, bottom hole pressures may be maintained on the sample at all times. The sampler is again disassembled and sterilized prior to making another trip into the well.

1.7, 2.125 and 3.0 inch outside diameter samplers are used to obtain 1 and 2 liter sample volumes.

ELEMENTS, ATOMIC NUMBERS AND WEIGHTS, VALENCE, AND THERMAL NEUTRON CAPTURE CROSS SECTIONS

Element	Symbol	Atomic Number (Z)	Atomic Weight (A)	Valence	Thermal Neutron Capture Cross Section * (Barns)
Hydrogen	H	1	1.008	+ 1, - 1	. 33
Helium	He	2	4.003	0	.0000
Lithium	Li	3	6.939	+1	.0376
Beryllium	Be	4	9.013	+2	.009
Boron	B	5	10.811	+3	758.86
Carbon	C	6	12.011	+2, +4, -4	.0034
Nitrogen	N	7	14.007	+1, +2, +3, +4, +5 ,-1,-2,-3	.075
Oxygen	0	8	15.999	-2	.0002
Fluorine	F	9	18.998	-1	.0098
Neon	Ne	10	20.183	0	.0038
Sodium	Na	11	22.898	+1	.400
Magnesium	Mg	12	24.120	+2	.0625
Aluminum	Al	13	26.982	+3	.232
Silicon	Si	14	28.086	+2, +4, -4	.1638
Phosphorous	P	15	30.974	+3, +4, -3	.190
Sulphur	S	16	32.065	+4, +6, -2	.49
Chlorine	Cl	17	35.457	-1, +1, +5, +7	33.338
Argon	Ar	18	39.946	0	.668
Potassium	K	19	39.102	+1	2.152
Calcium	Ca	20	40.080	+2	.455
Scandium	Sc	21	44.956	+3	25.000
Titanium	Ti	22	47.90	+2, +3, +4	6.401
Vanadium	V	23	50.942	+2, +3, +4, +5	4.800
Chromium	Cr	24	51.996	+2, +3, +6	3.074
Manganese	Mn	25	54.938	+2, +3, +4, +7	13.300
Iron	Fe	26	55.847	+2, +3	2.514
Cobalt	Co	27	58.933	+2, +3	37.5
Nickel	Ni	28	58.71	+2,+3	4.264
Copper	Cu	29	63.54	+1, +2	3.812
Zinc	Zn	30	65.38	+2	1.06
Gallium	Ga	31	69.72	+3	1.147
Germanium	Ge	32	72.60	+2, +4	1.470
Arsenic	As	33	74.92	+3, +5, -3	4.300
Selenium	Se	34	78.96	+4, +6, -2	12.0
Bromine	Br	35	79.916	-1, +1, +5	2.798
Krypton	Kr	36	83.80	0	31.0
Rubidium	Rb	37	85.48	+1	.7
Strontium	Sr	38	87.63	+2	1.2
Yittrium	Y	39	88.92	+3	1.3
Zirconium	Zr	40	91.22	+4	.18
Niobium	Nb	41	92.91	+3, +5	1.2
Molybdenum	Mo	42	95.95	+6	2.7
Technetium	Tc	43	97.00	+4, +6, +7	22.
Ruthenium	Ru	44	101.1	+3	2.6
Rhodium	Rh	45	102.91	+3	150.
Paladium	Pd	46	106.4	+2, +4	8.
Silver	Ag	47	107.870	+1	96.00

***Based on percent abundance in nature.**

Element	Symbol	Atomic Number (Z)	Atomic Weight (A)	Valence	Thermal Neutron Capture Cross Section * (Barns)
Cadmium	Cd	48	112.41	+2	7,000.00
Indium	In	49	114.82	+3	190.
Tin	SN	50	118.70	+2, +4	.62
Antimony	Sb	51	121.76	+3, +5, -3	5.7
Tellurium	Te	52	127.61	+4, +5, -2	4.7
Iodine	1	53	126.91	-I, +I, +5, +7	6.20
Xenon	Xe	54	131.30	0	35.
Cesium	Cs	55	132.91	+I	28.
Barium	Ba	56	137.36	+2	1.20
Lanthanum	La	57	138.92	+3	8.9
Cerium	Ce	58	140.13	+3, +4	.73
Praseodymium	Pr	59	140.92	+3	3.90
Neodymium	Nd	60	144.27	+3	46.
Prometheum	Pm	61	145.0	+3	
Samarium	Sm	62	150.35	+2, +2	5,600.
Europium	Eu	63	152.0	+2, +3	1,400.
Gadolinium	Gd	64	157.26	+3	46,000.
Terbium	Tb	65	158.93	+3	46.
Dysprosium	Dy	66	162.50	+3	930.
Holmium	Ho	67	164.94	+3	65.
Erbium	Er	68	167.20	+3	173.
Thulium	Tm	69	168.94	+3	127.
Ytterbium	Yb	70	173.04	+2, +3	37.
Lutetium	Lu	71	174.99	+3	112.
Hafnium	Hf	72	178.49	+4	105.
Tantalum	Ta	73	180.95	+5	21.
Tungsten	W	74	183.86	+6	19.2
Rhenium	Re	75	186.2	+4, +6, +7	86.
Osmium	Os	76	190.2	+3, +4	15.3
Iridium	Ir	77	192.2	+3, +4	440.
Platinum	Pt	78	195.09	+2,+4	8.8
Gold	Au	79	197.0	+I, +3	98.8
Mercury	Hg	80	200.61	+I, +2	380.
Thallium	Tl	81	204.39	+I, +3	7.0
Lead	Pb	82	207.19	+2, +4	.17
Bismuth	Bi	83	208.99	+3, +5	.034
Polonium	Po	84	209.	+2, +4	.003
Astatine	At	85	210.	- I	
Radon	Rn	86	222.	0	.72
Francium	Fr	87	223.	+I	
Radium	Ra	88	226.	+2	20.
Actinium	Ac	89	227.	+3	510.
Thorium	Th	90	232.04	+4	7.4
Protractinium	Pa	91	231.	+4, +5	260.
Uranium	U	92	238.03	+3, +4, +5, +6	2.7
Neptunium	Np	93	237.	+3, +4, +5, +6	Various Unstable
Pluthonium	Pu	94	244.	+3, +4, +5, +6	Isotopes
Americium	Am	95	243.	+3, +4, +5, +6	"
Curium	Cm	96	247.	+3, +4	"
Berkelum	Bk	97	247.	+3, +4	"
Californium	Cf	98	251.	+3	"

***Based on percent abundance in nature.**

UNITS AND CONVERSION FACTORS

multiply ——→ by ——→ to obtain
to obtain ←—— by ←—— divide

DISTANCE/ DEPTH/LENGTH	mm	0.039370	in
	cm	0.39370	in
		0.03281	ft
		.01	m
	in	25.40005	mm
		2.54000	cm
		0.02540	m
		0.08333	ft
	ft	30.48006	cm
		12.0	in
		0.3333	yd
		0.30480	m
	yd	91.44018	cm
		36.0	in
		3.0	ft
		0.9144	m
	rod	5.5	yd
	m	10,000,000,000.	Å
		1,000,000.	u
		1,000.	mm
		100.0	cm
		39.370	in
		3.2808	ft
		1.0936	yd
	km	3,280.83	ft
		1,000.0	m
		.62137	mi
	mi	5,280.0	ft
		1,760.0	yd
		1,609.34	m
		1.60934	km
		1.19599	yd^2
AREA	cm^2	0.15499	in^2
	in^2	6.4516	cm^2
	ft^2	929.0341	cm^2
		0.092903	m^2
	yd^2	9.0	ft^2
		0.83612	m^2
	m^2	1,549.9969	in^2
		10.76387	ft^2
		1.19599	in^2
	acres	43,560.0	ft^2
		4,840.0	yd^2
		4,046.873	m^2
		0.40468	Hectare
		0.00405	km^2
		0.0015625	mi^2
	hectare	2.47105	acres
		10,000.0	m^2
	km^2	247.104	acres
		0.386	mi^2

UNITS AND CONVERSION FACTORS

multiply ——→ by ——→ to obtain
to obtain ←—— by ←—— divide

	rod^2	30.25	yd^2
	mi^2	640.0	acres
		258.999	Hectares
		2.5899	km^2
VOLUME/CAPACITY	cm^3	1,000.0	mm^3
		0.001	1
		0.06 102	in^3
		0.0002642	gal
		0.00003531	ft^3
	in^3	16.387025	cm^3
		0.004329	gal
		0.01638	1
		0.0005787	ft^3
		0.0001031	bbl
	1	1,000.0	cm^3
		1,000.0	ml
		61.02705	in^3
		1.05 7	qt
		0.26417	gal (U.S.)
		0.03532	ft^3
	gal (U.S.)	3,785.0	cm^3
		231.0	in^3
		4.0	qt (U.S.)
		3.7853	1
		0.83268	gal (Imp.)
		0. 13368	ft^3
		0.02381	bbl (42)
		0.003785	m^3
	gal (Imp.)	4.5459	1
		1.20095	gal (U.S.)
	bbl (U.S.)	158.984	1
		42.0	gal (U.S.)
		34.973	gal (Imp.)
		5.61458	ft^3
		6.29 ÷ density of liquid = tons (metric)	
		0.9997	bbl (Imp.)
	bbl (Imp.)	159.031	1
		42.0112	gal (U.S.)
	ft^3	1,728.0	in^3
		28.31684	1
		7.4809	gal (U.S.)
		0.1781	bbl (42)
		0.037037	yd^3
		0.02831	m^3
	m^3	264.17	gal (U.S.)
		219.97	gal (Imp.)
		1.3079	yd^3
		35.314	ft^3
		6.290	bbl (42)

UNITS AND CONVERSION FACTORS

multiply ——→ by ——→ to obtain

to obtain ←—— by ←—— divide

Category	multiply / to obtain	by	to obtain / divide
	acre-ft	325,850.0	gal (U.S.)
		43,560.0	ft^3
		7,758.4	bbl (42)
		1,613.33	yd^3
		1,233.49	m^3
	yd^3	201.974	gal
		27.	ft^3
DENSITY/ CONCENTRATION	gm/cc	350.51	lb/bbl(42)
		62.42976	lb/cu ft
		8.34544	lb/gal (U,S.)
		.036127	lb/cu in
	lb/gal (U.S.)	42.0	lb/bbl (42)
		7.4809	lb/cu ft
		0.119826	gm/cc
	lb/cu ft	5.6146	lb/bbl (42)
		0.13368	lb/gal(U.S.)
		0.016018	gm/cc
	lb/cu in	27,680.	gm/cc
WEIGHT/MASS	grain	0.06479	gm
		0.00229	oz
	gm	15.43236	grain
		0.03528	oz
		0.00220	lb
	oz	437.5	grain
		28.34952	gm
		0.0625	lb
	kg	35.274	oz
		2.2046	lb
	lb	453.59237	gm
		16.0	oz
		0.4536	kg
	ton (short)	2,000.	lb
		0.90718	ton (metric)
		0.89286	ton (long)
	ton (metric)	2,204.62	lb
		1.10231	ton (short)
		0.98421	ton (long)
			≡6 bbls 17°oil
			≡7 bbls 42°oil
	ton (long)	2,240.0	lb
		1.12	ton (short)
		1.01605	ton (metric)
RESISTIVITY	ohm cm^2/cm	.01	ohms m^2/m
	ohm m^2/m	100.	ohms cm^2/cm
PRESSURE	psi	70.3067	gm/cm^2
		0.0703070	kg/cm^2
		0.0689474	bar
		0.0680458	atm
		14.6960	psi
		1.01325	bar

UNITS AND CONVERSION FACTORS

multiply ——→ by ——→ to obtain

to obtain ←—— by ←—— divide

Category	multiply / to obtain	by	to obtain / divide
	kg/cm^2	14.22333	psi
		0.980665	bar
		0.967842	atm
	atm	1,033.23	gm/cc
		1.03323	kg/cm^2
		14.6960	psi
	bar	1,000,000.	dynes/cm^2
		14.5038	psi
		1.01972	kg/cm^2
		0.986924	atm
HEAT/ENERGY	btu	1.05×10^{10}	ergs
		1,054.8	joules
		251.996	cal
	cal	4.19×10^7	ergs
		4.1840	joules
		0.003968	btu

TEMPERATURE

	°Fahrenheit	°Rankine	°Centigrade	°Kelvin
Water boils	212.	672.	100.	373.
68°F	68.	528.	20.	293.
60°F	60.	520.	15.56	288.56
Water freezes	32.	492.	0	273.
O°F	0.	450.	-17.8	255.
absolute zero	-460.	0	-273.	0

°F=1.8°C+32 °C=$^{0.56}$(°F-32) °K=°C+273 °R=°F+460

RESISTIVITY OF GEOLOGIC MATERIALS

Formation/Mineral	Resistivity in Ohms M^2/M (At STP Unless Otherwise Stated)
Sulphur	10^9-10^{16} (1.9×10^{15} @ 20°C, 9.5×10^9 @115°C)
Petroleum	10^9-10^{16}
Biotite	10^{14}-10^{15}
Sylvite	10^{14}-10^{15}
Mica	$<10^{14}$
Halite —(Common salt)	$<10^4$-10^{14}
Quarts	10^{12}-10^{14}
Muscovite	10^{11}-10^{12}
Calcite	10^7-10^{12}
Cinnabar	10^6-10^{10}
Sheelite	10^6-10^{10}
Anhydrite	10^4-10^{10}
Limonite	10^6-10^8
Sphalerite	10^5-10^7
Bauxite	10^2-10^8
Hematite	1.39×10^{-3}-1×10^6
Bituminous Coal	10-10^6
Basalt	8×10^2-10^5
Gabbro	8×10^2-10^5
Diabase	8×10^2-10^4
Gneiss	10^2-10^4
"Sub-bituminous coal"	10^2-10^4
Dolomite	1 - 7×10^3
Limestone ("Dense")	80 - 6×10^3
Lignite	4×10^3
Conglomerates	up to 3,000
Siderite	10-1,000
Sand	up to 1,000
Slate	up to 1,000
Marl	up to 600
Siltstone	up to 300
Peat	10-300
Argillite	1-300
Braunite	.01-100
Ilmenite	.01-100
Marcasite	.01-100
Shale	up to 15
Pyrolusite	1-10
Chalcopyrite	10^{-1}-10^{-3}
"Sulfides"	10^{-1}-10^{-3}
Anthracite Coal	10^{-3}-5 (Most below 1 ohm m^2/m)
Pyrite	10^{-1}-10^{-4}
Magnetite	10^{-2}-10^{-4}
Bornite	10^{-2}-10^{-6}
Galena	10^{-2}-10^{-5}
Pyrrhotite	10^{-4}-10^{-5}
Graphite	10^{-4}-10^{-6}
Glaucodote	10^{-4}-10^{-6}
Native [illegible]	less than 10^{-6}

NOTE: 1. [illegible]sistivity of most bedded formations will vary with the direction of measurement

CHEMICAL COMPOSITION (AVERAGE) OF FORMATION TYPES — (% WEIGHT)

CONSTITUENT	SANDSTONE (CLARKE)	LIMESTONE (STOKES)	DOLOMITE (PETTIJOHN)	GYPSUM (PETTIJOHN)	NORITE (TURNER)	SYNITE (IDDINGS)	GRANODIORITE (TURNER)	BASALT (TURNER)	GABBRO (TURNER)	DIORITE (IDDINGS)	DUNITE (IDDINGS)	DIABASE (TURNER)	GRANITE (TURNER)	GLAUCONITE (TWENHOFEL)	KAOLINITE (GRIM)	MONTMORIL-LONITE (GRIM)	ILLITE (GRIM)
SiO_2	78.33	5.19	5.60	0.40	52.05	60.26	73.4	48.03	51.22	63.04	40.12	52.48	71.88	53.61	45.65	52.38	50.38
TiO_2	0.25	0.08	0.08	---	0.21	0.32	0.2	3.93	1.59	0.37	0.28	0.83	0.38	---	0.80	0.12	0.33
Al_2O_3	4.77	0.81	1.07	2.97	17.24	18.27	14.1	14.77	14.49	16.19	0.97	14.63	15.13	9.56	37.37	18.31	28.97
Fe_2O_3	1.07	0.54	0.16	0.77	0.65	2.31	0.7	3.98	2.91	1.88	1.77	1.45	0.95	21.46	0.69	2.58	3.57
FeO	0.30	---	0.31	---	8.65	3.35	1.7	8.22	11.86	4.21	8.40	9.18	1.08	1.58	0.03	0.21	1.07
MnO	---	0.08	0.04	---	0.13	0.07	0.02	0.13	0.14	0.08	0.10	0.13	0.11	---	---	---	---
MgO	1.16	7.88	20.15	1.53	8.98	0.75	0.4	7.27	4.33	2.61	45.48	8.00	0.69	2.87	0.34	3.93	2.61
CaO	5.50	42.57	28.15	30.76	11.37	2.62	2.1	8.18	7.86	4.33	0.23	9.76	1.22	1.39	0.48	1.87	0.30
Na_2O	0.45	0.08	0.21	---	1.83	5.14	3.4	3.64	3.21	3.58	0.03	1.78	2.80	0.42	0.20	0.66	0.40
K_2O	1.31	0.33	0.08	---	0.40	5.46	3.5	1.34	1.05	1.99	0.06	0.90	3.94	3.49	0.63	0.31	6.48
H_2O	1.63	0.77	0.46	17.53	0.63	0.95	0.3	---	0.56	1.52	2.12	0.96	0.13	5.96	13.81	19.78	7.69
P_2O_5	0.08	0.04	0.44	---	0.12	---	---	0.51	0.23	0.34	---	0.08	0.18	---	---	---	---
BaO	0.05	---	---	---	---	---	---	---	0.01	0.04	---	---	0.08	---	---	---	---
CO_2	5.03	41.54	43.34	2.80	---	0.38	---	---	0.01	---	---	0.03	---	---	---	---	---
SrO	---	---	---	---	---	---	---	---	0.01	---	---	---	---	---	---	---	---
C	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
SO_3	0.07	0.06	---	43.78	---	---	---	---	---	---	---	---	---	---	---	---	---
S	---	0.09	0.09	---	---	---	---	---	0.08	---	---	---	---	---	---	---	---
ZrO_2	---	---	---	---	---	---	---	---	---	---	---	---	0.01	---	---	---	---
	100.00	99.98	100.16	100.54	100.28	99.88	99.92	98.98	99.14	100.18	99.13	100.19	98.41	100.34	100.00	100.15	99.80

POTASSIUM CONTENT OF GEOLOGIC MATERIALS

Material	Potassium Content by Weight (%) (Average)	(Range)
Sylvite	54	
Potash	44.9	
Langbeinite	20	
Microcline	16	
Kainite	15.1	
Carnallite	14.1	
Orthoclase	14	
Polyhalite	12.9	
Muscovite	9.8	
Biotite	8.7	
Illite	5.2	3.51-8.31
Arkose (sandstone)	4.6	4.4-5.1
Synite	4.53	
Glauconite	4.5	3.2-5.8
Granite	4.0	2.0-6.0
Norite	3.3	
Granodiorite	2.90	
Shale	2.7	1.6-9.0
Igneous rock	2.6	
Graywacke (sandstone)	1.8	1.2-2.1
Diorite	1.66	
Basalt	1.3	
Sandstone	1.1 (Cleans Sands much lower)	0-5.1
Gabbro	.87	
Diabase	.75	
Kaolinite	.63	0-1.49
Limestone	.27	0-0.71
Montmorillonite	.22	0-.60
Orthoquartzite (sandstone)	.08	0-0.12
Dolomite	.07	.03-0.1
Dunite	.04	
Sea Water	.035	

This table is presented to show the effects of formation potassium content on gamma ray response. About 0.012% of all natural potassium is radioactive (i.e., K-40) giving off a 1.5mev gamma ray upon disintegration. Approximately 20% of the gamma ray emissions from shale are caused by the isotope K-40. The remaining radiation from shales is generally caused by uranium and thorium series elements.

The average sandstone contains about 12% feldspar. Even orthoquartzite sands may contain 10% feldspar. "Although any kind of feldspar may be present the acid feldspars, particularly potash-bearing (orthoclase) varieties are most common" (Pettijohn).

A number of sandstones from California have been reported to contain an average of 50% feldspar. Arkosic sandstones are generally non-shaly and contain 25% or more feldspar derived from the disintegration of acid igneous rocks. Such formations have a high potassium content.

Graywacke sandstones are generally shaly and contain 33% or more easily destroyed minerals and rock fragments derived by rapid disintegration of basic igneous rocks, slates, and dark colored rocks. Such formations may contain considerable potassium but not in the quantity found in the arkosic sandstones.

GLOSSARY

a .... *constant in formation factor-porosity relationship ($F=a/\phi^m$)*
A .... *Atomic weight*
A .... *A current electrode used in electric logging*
α .... *SP reduction factor*
AM .... *Normal device electrode spacing*
AO .... *Lateral device electrode spacing*
APIGU .... *American Petroleum Institute Gamma Ray Unit (a standard)*
APINU .... *American Petroleum Institute Neutron Unit (a standard)*
B .... *Upper current electrode*
BHT .... *Bottom hole temperature (°F in U S A)*
CPS .... *Counts per second*
C .... *Centigrade or Celsius*
d_h .... *Borehole diameter*
d_i .... *Average diameter of invaded zone*
E .... *Voltage*
E_c .... *Electrochemical component of the SP*
EC .... *Electrical Conductivity*
E_k .... *Electrokinetic component of the SP (streaming potential)*
eV .... *Electron volts*
F .... *Formation-resistivity factor (equals RO/Rw)*
G .... *Geometric factor*
h .... *Bed thickness (feet in U S A)*
kHz .... *KiloHertz*
M .... *Potential electrode, normal device*
MN .... *Distance between the measuring electrode and its reference*
mC .... *MilliCurie*
mR .... *MilliRoentgen*
N .... *Resistivity reference electrode*
ppm .... *Parts per million (equals milligrams per liter)*
PR .... *Point resistance*
R .... *Resistivity in ohms-meters (ohm-m)*
R_i .... *Resistivity of invaded zone*
R_m .... *Resistivity of mud*
R_{mc} .... *Resistivity of mud cake*
R_{mf} .... *Resistivity of mud filtrate*
R_o .... *Resistivity of formation 100% saturated with formation water*
R_s .... *Resistivity of adjacent formation*

R_t ....*True formation resistivity*
R_w ....*Resistivity of formation water*
R_{we} ....*Calculated resistivity of formation water uncorrected for salinity or ion type (apparent formation water resistivity)*
R_{xo} ....*Resistivity of flushed zone*
SP ....*Spontaneous potential*
SSP ....*Static SP (the maximum possible SP for a given Rmf/RW)*
TC ....*Time constant*
TDS ....*Total dissolved solids*
ø ....*Effective porosity, in percent*
Σ ....*Neutron capture cross section*
Z ....*Atomic number*

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APPENDIX

Logging Specifictions

ALL LOGS

1. All logs and headings to comply with A.P.I. RP-38 standards for format and log scales. All pertinent well data to be recorded on log headings.
2. Calibration checks and electrical and mechanical zeros to be properly labeled.
3. All scale changes and/or mechanical adjustments noted on logs at proper depths.

ELECTRIC LOGS

1. Should consist of an S.P. curve and two resistivity curves which are calibrated in ohm-meters. At least one of the resistivity curves should be deep penetrating.
2. Rm, Rmf and corresponding temperature measured and recorded. These readings to be taken on a sample of drilling fluid circulated from the well immediately prior to logging.
3. All logs operated going in hole to check surface and downhole equipment.
4. When in doubt about log quality and if hole conditions permit, re-record part of the log for a repeatability check.

CALIPER LOGS

1. Tool to be calibrated immediately prior to logging with at least three gauge rings.
2. If well has surface pipe, check caliper for proper reading here.

NUCLEAR LOGS

1. When calibrating, using approved A.P.I. calibrators, record zeros, background and calibrator responses.
2. Record all log scale and/or zero changes when entering casings or at water levels.

For additional information please write to or call the following:

Principal Office

WELENCO
4817 District Blvd.
Bakersfield, CA 93313
(805) 834-8100
(800) 445-9914

Regional Offices

WELENCO
6992 Gregory Lane
Salinas, CA 93907
(408) 663-3116

WELENCO
2274 Freeman Drive
Claremont, CA 91711
(714) 625-1744

WELENCO
284 East Chilton Dr., Suite #2
Chandler, AZ 85225
(602) 926-2991

WELENCO
3630 El Rancho Drive
Sparks, NV 89433
(702) 673-5529

WELENCO
1313 Adams Court
Woodland, CA 95695
(916) 661-6161

WELENCO
1351 East Third Ave., No. H
Kennewick, WA 99336
(509) 582-8118

ENVIRONMENTAL SCIENCE & TECHNOLOGY

ES&T

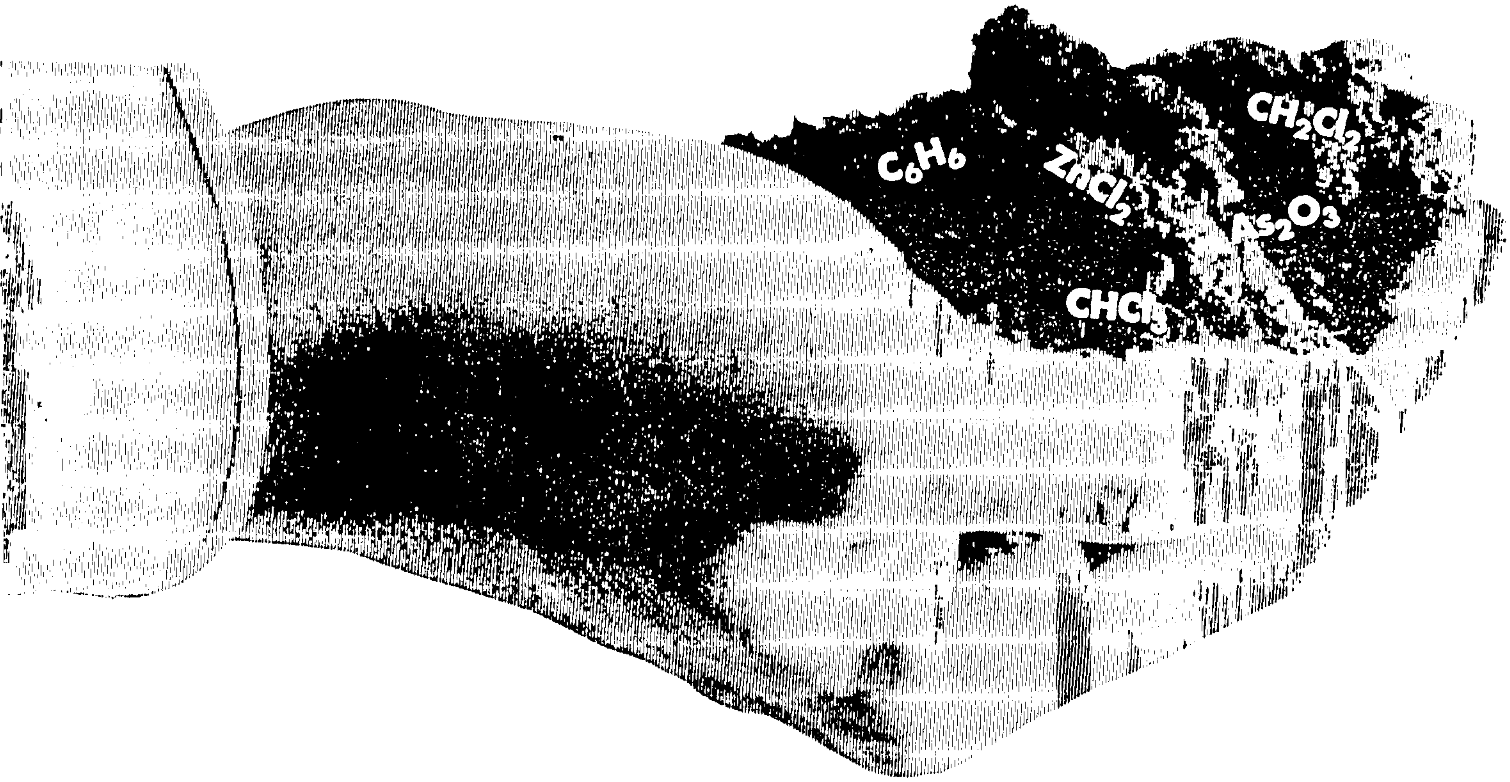
Soil-gas surveying techniques

Donn L. Marrin
Henry B. Kerfoot

Volume 22, Number 7
Pages 740-745

Soil-gas surveying techniques

A new way to detect volatile organic contaminants in the subsurface



Donn L. Marrin
La Jolla, Calif. 92037
Henry B. Kerfoot
Lockheed Engineering and Management Services Company
Las Vegas, Nev. 89119

Delineation and remediation of subsurface contamination have become a major focus of environmental science during the past five years. Conventional technologies available for subsurface investigations (e.g., monitoring wells and soil borings) always will be required to confirm and monitor subsurface contamination; however, quicker and less expensive techniques are useful for preliminary site evaluations. Soil-gas surveying is a technique that is applicable to a wide range of volatile organic compounds (VOCs) under a variety of geologic and hydrologic settings.

The most common uses of soil-gas data include planning monitoring well networks and defining plume boundaries for remedial action. Preliminary screening techniques are effective in selecting locations for detailed sampling and analysis. Site investigators can use results from a preliminary soil-gas survey to drill monitoring wells at locations within the boundaries of a VOC plume. Soil-gas investigations also can be used to identify sources of VOCs and to distinguish between soil and groundwater contamination (*1*). Chemical analysis of soil gases has recently been used to monitor solvent and fuel leaks from underground storage tanks.

In order to effectively design soil-gas surveys and interpret their results, the subsurface transport and fate of VOCs must be understood. These phenomena can have a profound impact on the presence and concentrations of VOCs in the soil atmosphere. Physical, chemical, and microbiological processes can be important in determining VOC concentrations in soil gas.

Physical processes

Organic compounds can undergo a variety of equilibrium and transport processes in the subsurface (*2–4*). The most important physical process affecting soil-gas surveys is solution/vapor equilibrium. Because of their relatively low solubilities and high vapor pressures, dissolved VOCs have a marked tendency to partition into the soil atmosphere. The physical law that quantitatively describes the solution/vapor equilibrium of VOCs is Henry's law. Henry's law constants are calculated by dividing the vapor pressure of a pure compound by its water solubility. This constant, when multiplied by the dissolved concentration in a solution, provides an estimate of the VOC concentration in the adjacent gas phase. Organic compounds with the highest Henry's law constants will partition most favorably from groundwater into the soil gases. The constants provide only a relative indication of solution/vapor partitioning in the field, for VOC equilibrium across the capillary fringe is affected by solute and matrix properties. Table 1 shows the most frequently encountered substances at Superfund sites and their Henry's law constants; most of these are VOCs amenable to soil-gas surveying. The aromatic and aliphatic components of gasoline have been identified as good candidate compounds for soil-gas analysis (*5, 6*).

TABLE 1
Most frequently identified substances at 546 Superfund sites

	Henry's law constant[a]		
	ppbv·L / µg[b]	Dimensionless[c]	Percent of sites
Trichloroethylene[d]	72	0.385	33
Lead and compounds	NA	NA	30
Toluene[d]	56	0.230	28
Benzene[d]	71	0.245	26
Polychlorinated biphenyls (PCBs)	<<1	~0	22
Chloroform[d]	40	0.111	20
Tetrachloroethylene[d]	123	0.588	16
Phenol	<<1	~0	15
Arsenic and arsenic compounds	NA	NA	15
Cadmium and cadmium compounds	NA	NA	15
Chromium and chromium compounds	NA	NA	15
1,1,1-Trichloroethane[d]	30	0.667	14
Zinc and zinc compounds	NA	NA	14
Ethylbenzene[d]	59	0.279	13
Xylenes[d]	32	0.203	13
Methylene chloride[d]	23	0.083	12
trans-1,2-Dichloroethylene[d]	77	0.333	11

[a]NA = not applicable.
[b]Gas-phase concentration (ppbv) ÷ liquid-phase concentration (µg/L).
[c]Gas concentration (µg/L) ÷ liquid concentration (µg/L).
[d]Amenable to soil-gas sampling.
Source: Reference 18.

Several theories have been proposed to describe the transport of volatile compounds from groundwater into the soil gas. Swallow and Gschwend (*7*) have formulated and laboratory-tested a steady-state model that predicts vertical migration of VOCs in the saturated zone based on transverse hydrodynamic dispersion. They hypothesized that VOCs are transported through the capillary fringe by the combined processes of dispersion and molecular diffusion. Other workers have considered the effects of episodic factors on vertical VOC transport. For example, Lappala and Thompson (*8*) have suggested that water table fluctuations may provide an important mechanism for transporting VOCs from groundwater into soil gas.

Once VOCs enter the soil gas, they diffuse in response to a chemical concentration gradient. Although advective processes or vapor density effects may locally influence VOC migration, gaseous diffusion is the predominant transport mechanism. According to steady-state models, vertical contaminant flux is proportional to the air-filled porosity of the vadose zone, the VOC diffusion coefficient, and the gas-phase concentration gradient. Vertical transport by diffusion predicts a linear increase in VOC concentration with depth, which has been confirmed in one field study (*9*). Subsurface geologic heterogeneities, soil porosity, moisture conditions, VOC concentrations in groundwater, and sorption equilibria can significantly affect VOC gradients in the vadose zone (*2, 10–12*). VOC concentrations in soil gas above any diffusion-limiting layer will be lower than concentrations below such a layer. Figures 1B and 1C show how subsurface and surface diffusion barriers can affect VOC concentrations. Such barriers include saturated clay layers, perched water, and pavement.

Biological/chemical processes

Degradation of VOCs in the subsurface can have a negative effect on the remote detection capabilities of soil-gas surveying. Oxidation can convert VOCs into nonvolatile or water-soluble compounds that are not amenable to soil-gas analysis. Hydrocarbon and halocarbon compounds have different susceptibilities to biological and chemical degradation. Hydrocarbons are readily oxidized under the aerobic conditions that are prevalent in the upper vadose zone. Aerobic microbiological oxidation in the subsurface has been measured in environments where the rate-limiting process was oxygen transport from the atmosphere (*13*).

Halocarbons are generally more resistant to aerobic degradation than hydrocarbons but can undergo anaerobic biodegradation. Compounds with minimal halogen substitution, such as chlorobenzene, can undergo aerobic as well as anaerobic degradation (*14*). Selective biodegradation of VOCs is probably related to environmental factors such as pH, redox potential (p*e*), and the composition of microflora in any particular soil. Figure 1D illustrates the possible effect of subsurface biodegradation on VOC concentrations in soil gas.

Sampling and analysis

Sampling techniques used in soil-gas surveying fall into two categories: grab sampling and passive sampling. Static grab sampling gives an instantaneous picture of the soil atmosphere at a particular subsurface location, whereas passive sampling provides an integrated measure of VOC concentrations over time.

Grab sampling. Static grab sampling is a technique whereby the samples are collected from a quiescent soil-gas sample. Dynamic grab sampling, on the other hand, involves samples being collected from a moving stream of soil gas that is pumped through a hollow probe. The strategy behind grab sampling is to collect soil gas as quickly as possible from a specific depth. Grab samples typically are analyzed on-site in order to permit the use of real-time data in selecting sampling locations and

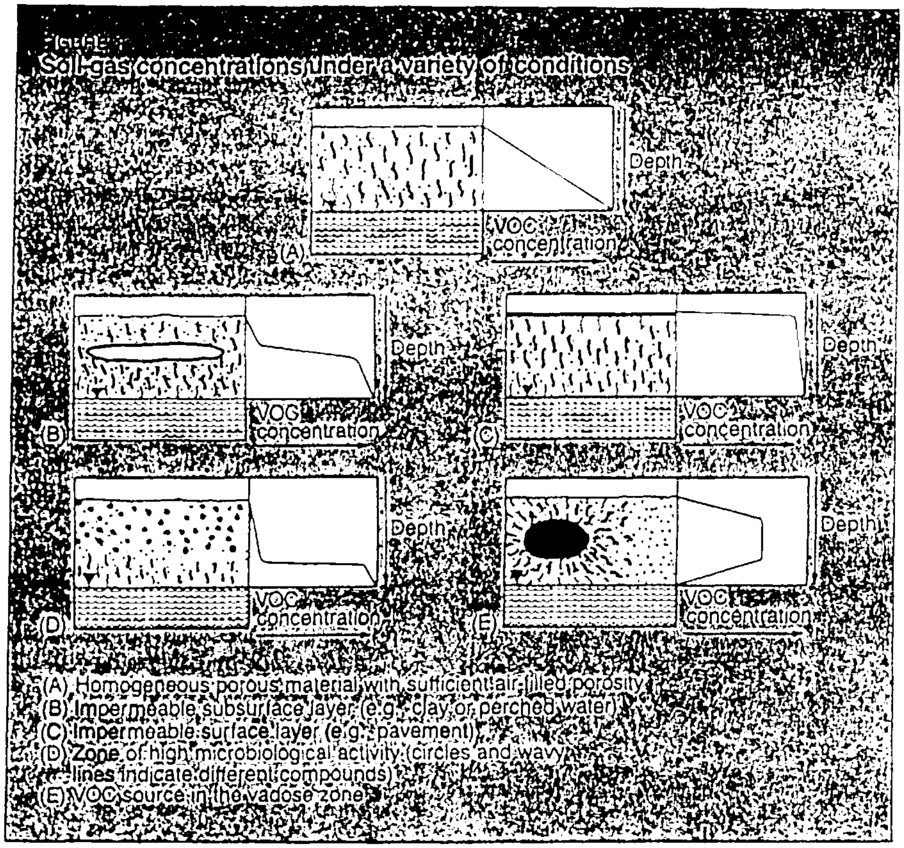


Figure 1.
Soil-gas concentrations under a variety of conditions

(A) Homogeneous porous material with sufficient air-filled porosity
(B) Impermeable subsurface layer (e.g., clay or perched water)
(C) Impermeable surface layer (e.g., pavement)
(D) Zone of high microbiological activity (circles and wavy lines indicate different compounds)
(E) VOC source in the vadose zone

to minimize the problems associated with handling and transporting gas samples.

The advantage of grab-sampling techniques combined with on-site gas chromatography is that results are available in a matter of minutes. Perhaps the greatest disadvantage associated with dynamic sampling is the perturbation of local VOC concentrations as a result of soil-gas pumping. In addition, the results obtained from any grab-sampling method are highly depth-dependent. The selection of appropriate sampling depths is based on site-specific factors (e.g., moisture conditions, air-filled porosity, VOC concentrations, and depth to groundwater) as well as compound-specific factors (e.g., solubility, volatility, and degradability).

On-site analysis of soil-gas samples can be performed either with mobile laboratories or with portable instruments. Mobile laboratories can provide detailed chemical data as well as convenience because packing and shipping of samples is not necessary. On the other hand, mobile laboratories require a large initial investment and the presence of an analytical chemist. Although portable instruments are less sensitive and versatile than mobile labs, they are relatively small and inexpensive. Furthermore, they can be operated by a trained field technician.

Passive sampling. Passive sampling utilizes a charcoal sorbent to trap contaminants that diffuse through the soil gases. Passive charcoal samplers are buried in the shallow soil for as long as one month and then retrieved for analysis. Once the VOCs are sorbed onto the charcoal, samples are transported to a laboratory where desorption and chemical analyses are performed. Both solvent desorption (*15*) and pyrolysis techniques (*16*) have been used to desorb soil-gas VOCs prior to analysis.

The advantage of passive soil-gas sampling is that field operations require minimal training, and the technique averages out concentration fluctuations caused by changes in environmental conditions. The major disadvantage of passive samplers is that results are not available for days to weeks because desorption and laboratory analysis are both time consuming. Additionally, passive sampling may not be appropriate for VOCs that have boiling points below approximately 5 °C or for compounds that are prone to thermal decomposition during pyrolysis (*17*).

Case studies

A shallow soil-gas investigation of a solvent plume was conducted in a suburban area where the underlying groundwater (at a depth of approximately 30 m) was contaminated with several chlorinated solvents. The investigation was designed to delineate the areal extent of 1,1,1-trichloroethane (TCA), which had been discovered at concentrations as high as 3000 µg/L in groundwater wells located downgradient from the source. Prior to the soil-gas survey, there were no data regarding plume characteristics or the downgradient extent of TCA contamination. The results of grab sampling at 1.5 m below ground surface and soil-gas analysis by gas chromatography/electron capture detection (GC/ECD) are shown in Figure 2.

Figure 2 indicates that the most concentrated portion of the TCA plume (50 µg/L contour) lies just east of the source. The soil-gas plume is oriented along a definite north–south axis, indicating TCA migration in a predominantly southerly direction from the source. Boring logs indicate that the regional geology consists of sand and gravelly sand with isolated perched water zones that are underlain by clay. Coarse-grained soils (e.g., sands and gravels) are optimal for the diffusive movement of gaseous contaminants because they are well drained and have high air-filled porosities.

Soil gas was sampled adjacent to 11 wells in the vicinity of the source to compare TCA concentrations in soil gas with those in groundwater (Figure 3). A correlation coefficient of 0.88 was calculated using seven of the 11 points (99% significance). The remaining four points (W-5 through W-8) were excluded from the regression analysis because they were clustered in an area underlain by perched water. Perched water can act as a barrier to VOC diffusion, creating low VOC concentrations in soil gas between the barrier and the ground surface (see Figure 1B). The soil-gas/groundwater concentration ratios of the four points in the area of perched water were low compared with the majority of points (Figure 3). Anomalously low soil-gas/groundwater ratios usually indicate either the presence of a barrier to gaseous diffusion (e.g., perched water or clay lenses) or high levels of biodegradation in the vadose zone. Conversely, anomalously high soil-gas/groundwater ratios suggest that probes have been sampled near a spill or subsurface leak.

The soil-gas survey provided resolution of plume characteristics that could not be achieved by sampling groundwater wells. The presence of several anomalous soil-gas concentrations did not preclude accurate mapping of subsurface contamination because of the numerous sampling points. Results were used to select optimal locations for monitoring wells and to confirm the association between TCA contamination at the source area and at wells located as far as 2 km downgradient. Approximately 130 soil-gas samples were collected and analyzed during seven days of field investigation. The entire

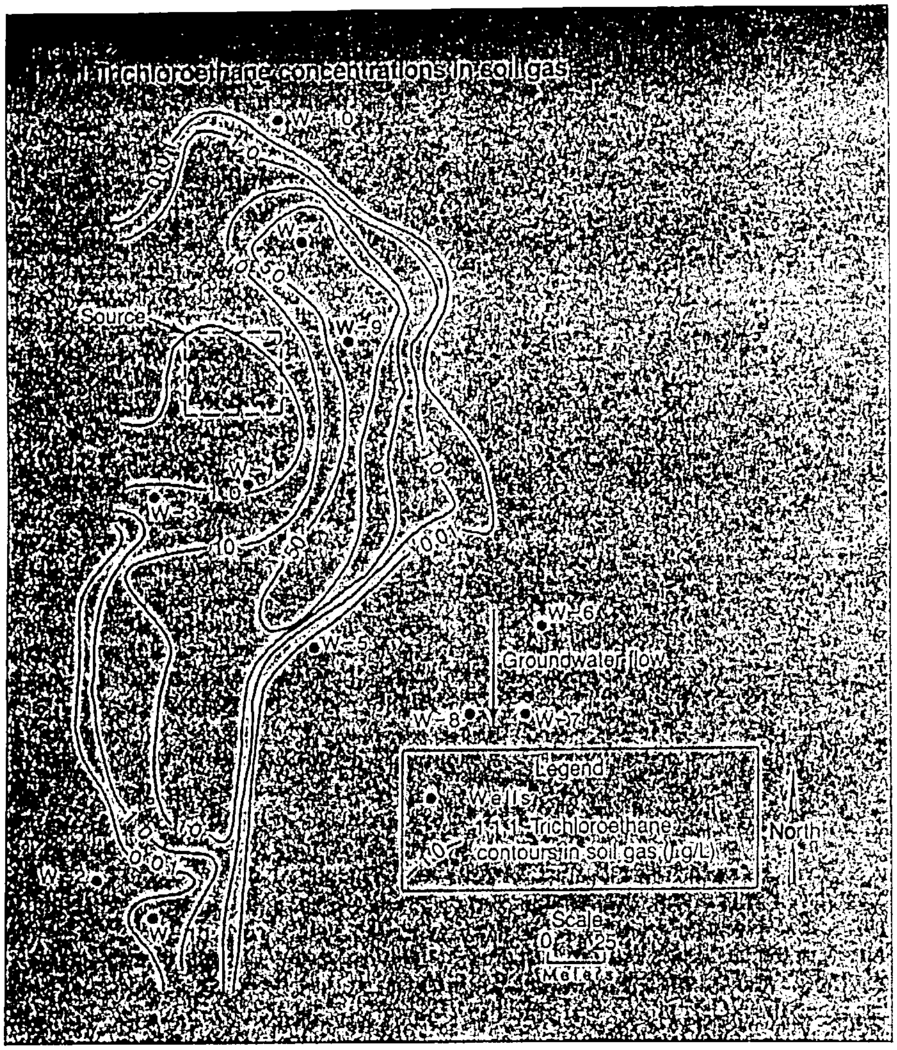


FIGURE 2
1,1,1-Trichloroethane concentrations in soil gas

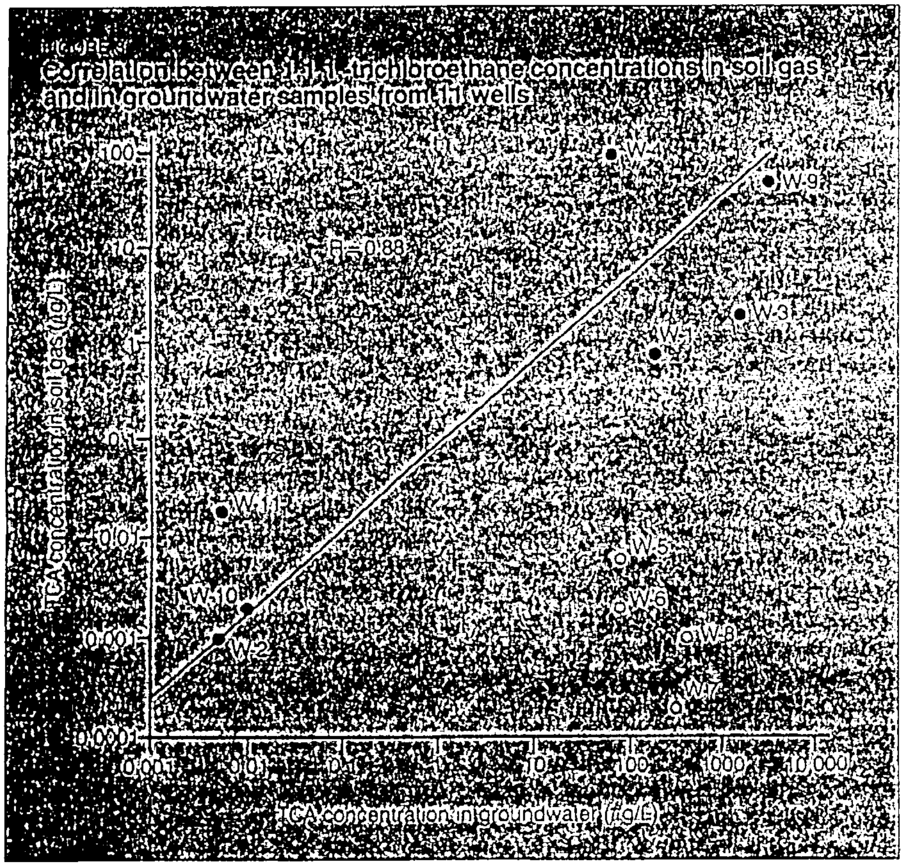


FIGURE 3
Correlation between 1,1,1-trichloroethane concentrations in soil gas and in groundwater samples from 11 wells

soil-gas survey was completed for approximately the same cost as that required to install and sample three monitoring wells.

A second case history involves a soil-gas survey that was performed to delineate subsurface contamination from a leaking underground gasoline storage tank. Service station records indicated that approximately 70,000 L of unleaded gasoline leaked from the tank during a one-year period. Private wells and exploratory bore holes suggested the presence of subsurface gasoline contamination, which was migrating to the east. To evaluate the extent of subsurface migration, a soil-gas survey was performed and confirmatory bore holes were drilled.

Groundwater was present at depths ranging from 8 to 30 m beneath the ground surface. Preliminary soil-gas samples were collected from depths of 0.67 m and 2.2 m below the ground surface to select an appropriate sampling depth. The 2.2-m depth was selected because hydrocarbons could not be detected in soil gas at the shallower depth; this phenomenon was attributed to aerobic biodegradation of the hydrocarbons in the shallow soil. Soil-gas sampling probes were installed on a grid pattern within a 400×700-m area and were analyzed on site with a portable gas chromatograph and photoionization detector. Figure 4 shows the soil-gas sampling locations.

Figure 4a shows the areal extent of gasoline contamination as indicated by the analysis of soil core and groundwater samples. The results of soil-gas analyses for isooctane and butane are shown in Figures 4b and 4c, respectively. Concentrations of butane and isooctane in soil-gas samples predicted the areal extent of the gasoline plume. These two compounds have been determined in laboratory studies to be more resistant to biodegradation than other components of gasoline (*18*). An anomalous low-concentration zone is located near the source of the soil-gas plumes (Figure 4b and 4c). Anomalously low soil-gas concentrations were observed for all hydrocarbon compounds in this zone, which is near a septic tank drain field.

The drain field probably has higher biodegradation rates than other sites in the survey area because of its high bacterial concentrations. VOC concentrations in soil gas may be affected not only by increases in biological activity but also by high moisture levels and a significant organic phase in the soil underlying the drain field. Gasoline hydrocarbons partition out of the gaseous phase and into aqueous or organic phases of the soil in accordance with their physical properties. In addition, the effective diffusion of volatile hydrocarbons in soil gas decreases as the percentage of water-filled pores increases.

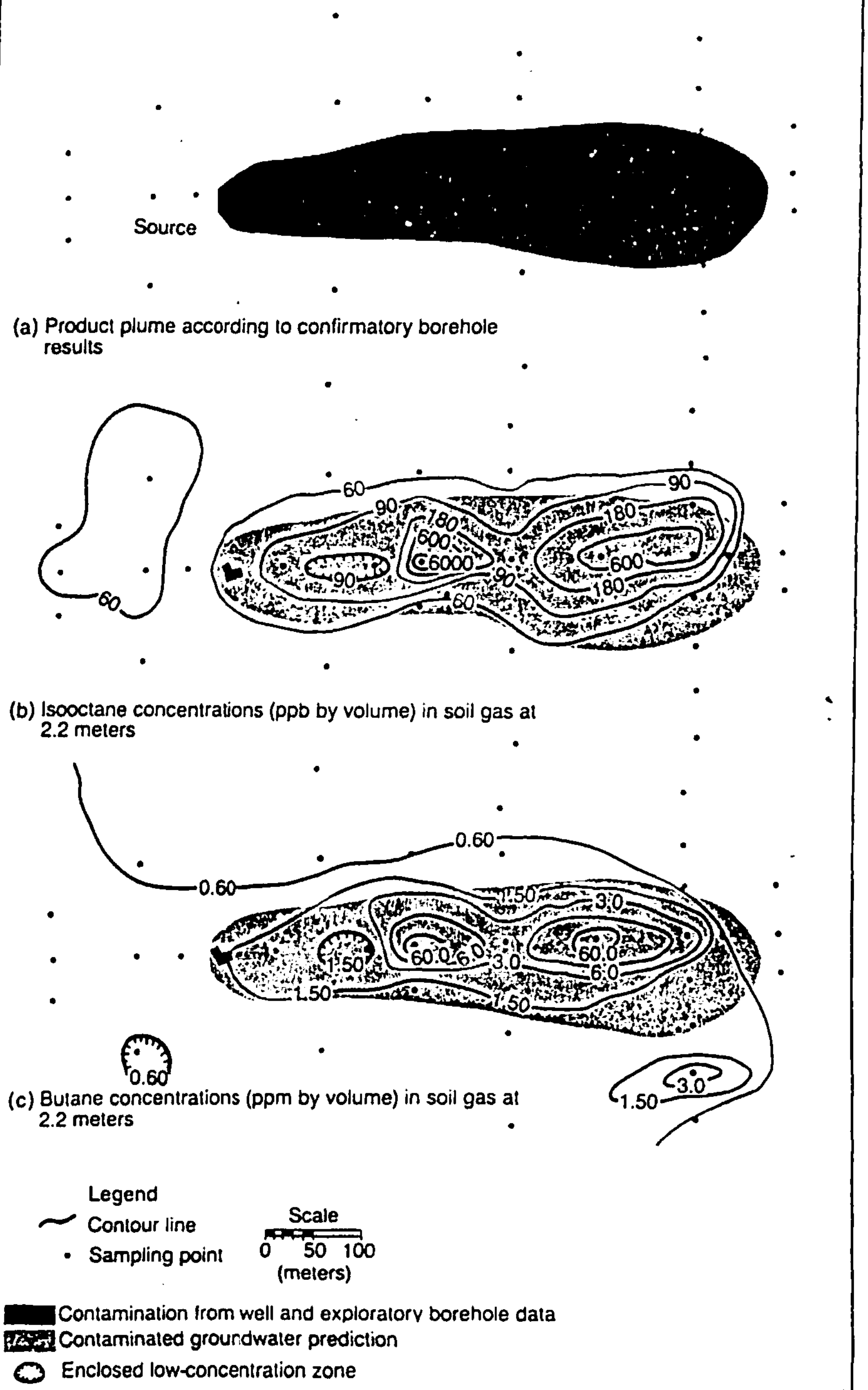
Summing up

Soil-gas surveys serve as an effective reconnaissance tool because numerous data points can be sampled over a short time period for a relatively low cost. Both grab-sampling and passive-sampling techniques have been used to evaluate the magnitude and lateral extent of VOC contamination and to locate sources of subsurface contamination. Soil-gas surveying has an advantage over geophysical techniques for detecting shallow contamination because identifiable compounds rather than indirect physical changes in the subsurface are measured. Moreover, soil-gas techniques are sensitive both to dissolved VOCs and to pure product layers.

Soil-gas surveying is applicable to the most volatile organic compounds, which pose a major threat to groundwater supplies. VOCs are present at a majority of hazardous-waste sites and are generally more mobile than the nonvolatile organic compounds (e.g., PCBs, polycyclic aromatic hydrocarbons, and pesticides). Theoretically, soil-gas concentrations of compounds produced by in situ degradation of less volatile contaminants can be used to detect subsurface organic contamination. In fact, use of such techniques for detection of groundwater contamination and fuel tank leakage have been recently reported (*19, 20*). Soil-gas techniques will never replace the monitoring functions served by groundwater wells and soil borings, and, in fact, were developed to enhance the effectiveness of these conventional methodologies.

Similar to other remote detection techniques, soil-gas surveying is effective only for specific types of subsurface contamination and must be interpreted with careful regard to the physical chemistry of contaminants and the hydrogeologic setting. Broad generalizations concerning flux rates, degradation potentials, or soil-gas/groundwater correlations should be avoided in favor of case-by-case interpretations. Although the theory behind sampling VOC concentrations in soil-gas is straightforward, the data interpretation associated with these surveys is often complex.

FIGURE 4
Subsurface contamination from a leaking gasoline tank



(a) Product plume according to confirmatory borehole results

(b) Isooctane concentrations (ppb by volume) in soil gas at 2.2 meters

(c) Butane concentrations (ppm by volume) in soil gas at 2.2 meters

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Acknowledgment

Although the research described in this article has been funded wholly or in part by the U.S. Environmental Protection Agency through Contract 68-03-3249 to Lockheed Engineering and Management Services Company, Inc., it does not necessarily reflect the views of the agency and no official endorsement should be inferred.

This article has been reviewed for suitability as an *ES&T* feature by Thomas E. Spittler, EPA Region 1 Laboratory, Lexington, Mass. 02173; and by David K. Kreamer, Arizona State University, Tempe, Ariz. 85287.

Donn L. Marrin (l) is an independent consultant and research scientist specializing in hydrology, aquatic/environmental chemistry, and the behavior of subsurface organic contaminants. He has designed and evaluated soil-gas investigations, vadose zone studies, and vapor extraction/monitoring systems for in situ remediation of sites throughout the United States. He holds a Ph.D. in hydrology and water resources from the University of Arizona as well as degrees in the biochemical and environmental sciences from the University of California.

Henry B. Kerfoot (r) is a project manager at Lockheed Engineering and Management Services Company in Las Vegas, Nev. His current research interests include vadose zone techniques for detection of subsurface contamination, indirect indicators of groundwater contamination, and soil-gas cleanups. He has designed and evaluated soil-gas surveying systems for mapping plumes and for storage tank leak detection. In 1987 Kerfoot received Lockheed's Robert E. Gross Award for his work in soil-gas surveying. He holds degrees in chemistry from The Johns Hopkins University and Florida State University.

4.0 PROCEDURES

4.1 Introduction

The assessment of aquifer characteristics is vital to any investigation of groundwater contamination. Pumping tests are one of the primary methods to quantitatively estimate aquifer characteristics. This method also most closely simulates actual pumping during typical groundwater remediation scenarios.

Pumping tests may be conducted to determine (1) the performance characteristics of a well and (2) the hydraulic parameters of an aquifer. For a well-performance test, yield and drawdown are recorded so that the specific capacity can be calculated. These data, taken under controlled conditions, give a measure of the productive capacity of the completed well and also provide information needed for the selection of pumping equipment. An accurate test of a well before the pump is purchased pays for itself by assuring selection of a pump that will minimize power and maintenance costs. Many times, high pumping costs and unsatisfactory pump performance are erroneously charged to the well when these conditions really stem from an improperly selected pump.

The second purpose of pumping tests is to provide data from which the principal factors of aquifer performance -- transmissivity and storage coefficient -- can be calculated. This type of test is called an aquifer test because it is primarily the aquifer characteristics that are being determined, even though the specific capacity of the well can also be calculated. Aquifer tests will predict (1) the effect of new withdrawals on existing wells, (2) the drawdowns in a well at future times and different discharges, and (3) the radius of the cone of influence for individual or multiple wells. Aquifer test data are more valuable today because a better understanding of groundwater hydraulics now exists and new sophisticated methods of data retrieval and analysis have been developed.

An aquifer test consists of pumping a well at a certain rate and recording the drawdown in the pumping well and in nearby observation wells at specific times. There are two primary types of aquifer tests: constant discharge tests and step-drawdown tests. In a constant discharge test, the well is pumped for a significant length of time at one rate, whereas in a step-drawdown test the well is pumped at successively greater discharges for relatively short periods. Data from both types of aquifer pumping tests can be analyzed to determine important hydraulic characteristics of an aquifer and the well. The results from properly conducted tests are very important tools in groundwater investigations.

Measurements required for both well tests and aquifer tests include the static water levels just before the test is started, time since the pump started, pumping rate, pumping levels or dynamic water levels at various intervals during the pumping period, time of any change in discharge rate, and time the pump stopped. Measurements of water levels after the pump is stopped (recovery) are extremely valuable in verifying the aquifer characteristics calculated from the pumping phase of the test.

4.1 Introduction (continued)

For well tests, the yield and drawdown are measured after a certain time has elapsed. Although aquifer testing is more involved than well testing, the methods presented below for determining yields and measuring drawdown are used in both well and aquifer pumping tests. These methods and procedures apply primarily to constant discharge and step-drawdown aquifer tests.

Other types of tests can be used depending upon the aquifer and the logistic situation under which the test is being performed. The types of tests to be used would depend upon site-specific criteria and could include constant drawdown tests, monitoring formation pressure changes after they have been disturbed (drill-stem tests), or by controlled injection. These types of tests are not commonly performed during hazardous waste investigations and therefore are not discussed further.

4.2 Decontamination

Prior to lowering the equipment into any well, decontaminate each item using the following procedure:

- o Wash the pump and associated hoses, transducers, water level indicator, cable, and all other associated equipment that may enter the well with laboratory-grade detergent and tap water. Pump the detergent mixture through the pump and hoses for a minimum of five minutes.
- o Rinse the items thoroughly with tap water. Pump tap water through the pump hoses for a minimum of five minutes.
- o Rinse the items with reagent-grade distilled water.
- o Rinse the items with laboratory-grade methanol.
- o Rinse the items with reagent-grade distilled water.
- o Place the equipment in a polyethylene bag or cover in some similar way to prevent contamination during storage or transit.

4.3 Pre-Test Data Recording

Complete the applicable portions of Exhibit 6.2-1 Aquifer Test Data prior to conducting the aquifer test. Use a separate Exhibit page for each well. Also, obtain the following information from existing logs for each well to be used in the test prior to performing the test:

4.3 **Pre-Test Data Recording (continued)**

- o Casing diameter
- o Borehole diameter
- o Location of surveyed measuring point
- o Total casing depth
- o Static water level of each monitor well
- o Screen depth and interval
- o Filter pack depth and interval
- o Lithology of screened interval

Obtain a topographic and/or facility map of the site, if available. Based upon a review of the maps, identify the wells (in addition to the well to be pumped) that should be monitored during the test.

For each well of interest, identify access constraints: location with respect to roads, buildings, well-head locking devices. Obtain names of site contacts necessary to obtain access to wells. If wells are in a parking lot or roadway, make sure these areas will be controlled during testing.

Assemble the equipment necessary to conduct the aquifer pumping test. A list of useful equipment is presented in Exhibit 6.2-2 Aquifer Testing Equipment List.

4.4 **Pumping Test Design.** Aquifer testing and analysis methods are generally based upon the following assumptions:

- o The aquifer is homogenous and isotropic.
- o The aquifer is infinite in extent in the horizontal direction from the well and has a constant thickness.
- o The well screen fully penetrates the aquifer.
- o Groundwater flow within the aquifer and pumped well is laminar.
- o The initial static water level is horizontal.

Although these assumptions seem to limit pumping test data analysis, in reality they do not. Most aquifers do not have a constant hydraulic conductivity or transmissivity, but the average transmissivity can readily be obtained from a pumping test.

Pumping tests will not produce accurate data unless the tests are methodically conducted. In order to assure the reliability of the test data, pump the test well for several hours a few days before the actual test is conducted. As far as is practical, determine the following criteria:

4.4 Pumping Test Design (continued)

- o The maximum anticipated drawdown. (For most pumping tests, a major portion of the drawdown will occur in the first few hours of pumping.)
- o An estimate of the total volume of water to be produced from the pumping test. (Appropriate disposal methods must be well thought out before any pumping can occur.)

Never begin the actual pumping test until water levels in the aquifer have returned to normal (pre-test) static levels.

The accuracy of drawdown data taken during a pumping test depends upon the following:

- o Maintaining a constant yield during the test.
- o Measuring the drawdown carefully in the pumping well and observation wells.
- o Taking drawdown readings at appropriate time intervals.
- o Evaluating how changes in barometric pressures, stream levels, and tidal oscillations affect drawdown data.
- o Comparing recovery data with drawdown data taken during the pumping portion of the test.
- o Continuing the pumping test for minimum of 24 hours for a confined aquifer and 72 hours for an unconfined aquifer during constant discharge tests. For step-drawdown tests, 24 hours is usually sufficient for either type of aquifer.

The accuracy of data taken from the pumping well is usually less reliable because of turbulence created by the pump. Therefore, measure drawdown from as many observation wells within the expected zone of pumping influence as is practicable. Furthermore, drawdown data from an observation well are required to calculate the storage coefficient accurately, whereas transmissivity values may be calculated on the basis of drawdown data taken from either a pumping or observation well.

Observation wells should be just large enough to allow accurate and rapid measurement of water levels. Small-diameter wells are best because the volume of water contained in a large-diameter observation well may cause a time lag in drawdown changes.

When observation wells are too close to the pumped well, the drawdown readings may be affected by the stratification of the aquifer. Stratification distorts the distribution of hydraulic lead and drawdown in the vicinity of the pumped well during the aquifer test.

4.4 Pumping Test Design (continued)

For unconfined aquifers, observation wells should be no farther than 100 to 300 feet from the pumped well. For thick confined aquifers that are considerably stratified, observation wells should be within 300 to 700 feet from the pumped well.

4.5 **Background Water Level Measurements.** The objective of background measurements is to identify the presence of any naturally-occurring static water influences (e.g., diurnal) that may be confused as drawdown changes related to the pumping test. Perform the following steps to record background water levels:

- Measure water levels in wells expected to be influenced by pumping starting at least one week prior to the actual pumping test start date.
- Select several wells to place transducer probes into and record the background water levels with an electronic data logger.
- Use an electronic water level indicator to measure water levels in wells with no transducer probes.
- Program the data logger to record water levels every hour during the background measurement period.
- Plot water level change versus time to examine the data.
- Measure all water levels to within 0.01 foot.

4.6 **Step-Drawdown/Recovery Test.** Perform the following steps to conduct a step-drawdown test:

- Measure depth to static groundwater in the extraction well and all selected monitor wells. Include depth to the bottom of each well casing to check and record depth to accumulated fines or possible well obstructions. Record all measurements on Exhibit 6.2-1 Aquifer Test Data. Use a separate Exhibit page for each well.
- Install the test pump to the desired depth in the extraction well if it was not previously installed during pre-test pumping operations. (Remember to temporarily remove the transducer probe from the extraction well to avoid entanglement.) Depending on site restraints, place the pump above the bottom of the well to avoid pumping fines that have accumulated on the bottom of the well. This will prolong the operating life of the pump. Keep the pump intake at least three (3) feet above the bottom of the well, if possible.
- Reinstall the transducer probe in the extraction well.

4.6 Step-Drawdown/Recovery Test (continued)

- Program the data logger for logarithmic cycle measurements so that water-level measurements are recorded at the times shown in Exhibit 6.2-3 Time Intervals for drawdown measurement in a pumped well.
- Synchronize all watches of observers with the data logger's interval clock.
- Measure and record water levels in all wells.
- Start the electronic data logger.
- Start the pump at the predetermined initial discharge rate.
- Measure water levels in all wells after pumping starts. Record times on Exhibit 6.2-1, Aquifer Test Data. Exhibits 6.2-3 and 6.2-4 provide suggested time measurement intervals. As the test progresses, one person can perform the majority of the measurements. Always record these measurements as backup, in case the electronic data logger fails.
- Ideally, the step-drawdown test will employ several different discharge rates with each subsequent flow rate greater than the prior flow rate. Because the minimum flow any submersible pump can maintain is approximately 0.1 gpm (gallons per minute), never attempt to start an initial flow rate below 0.5 gpm, otherwise pump damage may occur.
- Consider the water level in the pumping well when selecting the next pumping step. It is better to select less than a double increase in flow rate than to dewater the well during the step-drawdown test. Refer to Exhibit 6.2-5 Aquifer Test Discharge Rate Criteria for optimum pumping rates during the step-drawdown test.
- Maintain the current flow rate if no increase in the flow rate during the test can be sustained by the well beyond a first step. Prior to dewatering, shut off the pump, allow the well to fully recover (perform recovery test), and start the test over with a substantially lower discharge rate, if possible.
- The duration of a step depends on the observed water level in the pumping well. The target duration of each step is at least 60 minutes. If the water level in the test does not change by more than 0.1 foot after 10 minutes of pumping for a particular step, increase the discharge to the next step. If the water level in the test well comes within a foot of the top of the pump, then pumping should be eased to prevent dewatering and possible pump damage. If within a step, the pumping level reaches equilibrium (maintains a steady level), maintain the flow rate for at least 30 minutes. Usually such cases indicate a large transmissivity or recharge may be occurring.

4.6 Step-Drawdown/Recovery Test (continued)

Perform the following steps over the course of the test:

- o Maintain discharge rates for each step within 10 percent (make sure the flow meter is not fluctuating abnormally). Air bubbles in the pump discharge must be minimized.
- o Calculate drawdown (actual - static level) during the test.
- o Do not change water level measurement devices during a test.
- o Note the actual time on Exhibit 6.2-1 Aquifer Test Data, that the discharge rate in the pumped well is increased and when the pump is shut off. Note any other unusual and routine occurrences on the Exhibit as well.
- o Plot all data on semilog graph paper in the field, where the x-axis is time (minutes) since pumping began on the log scale and the y-axis is drawdown (feet) in the arithmetic scale.

4.6.1 Well Recovery Test (step drawdown). The recovery portion of the step-drawdown pumping test begins after pumping ceases. Perform the following steps for recovery testing:

- o Measure water levels in all wells.
- o Before the pump is shut off, prepare the electronic data logger for restart of the logarithmic cycle.
- o When the pump is shut off, immediately re-start the electronic data logger and begin water level measurements per the intervals outlined in Exhibits 6.2-3 and 6.2-4.
- o Continue monitoring water level recovery until water levels in all wells do not change more than 0.01 foot over a 20 minute interval.
- o Terminate recovery measurements if the water level returns to the static level. (Do not remove the pump from the well until the recovery test is complete.)

4.7 Constant Discharge Test

A constant discharge pumping test is used to evaluate the transmissivity (T) and storage coefficient (S) of an aquifer. These characteristics can be calculated using various equations tailored to site-specific hydrogeologic conditions. In addition to T and S, a constant discharge test can aid in determining several other aquifer characteristics:

- o Predicted drawdown (s) at any time (t).
- o Predicted drawdown (s) at any distance within the cone of depression that surrounds the pumping well.
- o Predicted drawdown (s) at any discharge rate (Q).

Conduct a constant discharge pumping test for a minimum of 24-hours in confined aquifers and a minimum of 72-hours in unconfined aquifers or until equilibrium water levels are reached. Measure water level recovery in all wells after pumping ceases.

Perform the following steps to conduct a constant discharge pumping test:

- o Perform background water level measurements as outlined in Section 4.5 of this procedure.
- o Perform the test setup and water level measurements as outlined in Section 4.6 of this procedure. The actual performance of a constant discharge test is similar to a step-drawdown test except that a constant discharge test uses only one discharge rate for the entire test.
- o Determine the optimum discharge rate for the constant drawdown test with the results from the step-drawdown test. Ideally, the constant drawdown discharge rate is the highest rate that will preclude the pumping well from dewatering for at least 1440 minutes (1 day) of pumping.
- o Synchronize all watches of observers with the data logger internal clock.
- o Measure and record water levels in all wells.
- o Start the electronic data logger.
- o Start the pump at the predetermined discharge rate.
- o Measure water levels in all wells after pumping starts. Record the water levels on Exhibit 6.2-1, Aquifer Test Data. Exhibits 6.2-3 and 6.2-4 provide suggested time measurement intervals. As the test progresses, one person can perform the majority of the measurements. Always record these measurements as backup in case the electronic data logger fails.

4.7 Constant Discharge Test (continued)

Perform the following actions over the course of the test:

- o Maintain the discharge rate within 10 percent (make sure the flow meter is not fluctuating abnormally). Air bubbles in the pump discharge must be minimized.
- o Calculate drawdown (actual - static level) during the test.
- o Do not change water level measurement devices during a test.
- o Note the actual time on Exhibit 6.2-1 Aquifer Test Data, that the discharge rate in the pumped well is adjusted, if required, and when the pump is shut off. Note any other unusual and routine comments on the Exhibit as well.
- o Plot all data on semilog graph paper in the field; where the x-axis is time (minutes) since pumping began on the log scale and the y-axis is drawdown (feet) on the arithmetic scale.

4.7.1 **Well Recovery Test (constant discharge).** The recovery portion of the constant drawdown pumping test begins after pumping ceases. Perform the following steps for recovery testing:

- o Measure water levels in all wells.
- o Before the pump is shut off, prepare the electronic data logger and begin water level measurements per the intervals outlined in Exhibits 6.2-3 and 6.2-4.
- o Shut the pump off and immediately start the data logger.
- o Continue monitoring water level recovery until water levels in the wells do not change more than 0.01 foot over a 20 minute interval.
- o Terminate recovery measurements if the water level returns to the static level. (Do not remove the pump from the well until the recovery test is complete.)

4.8 Review

Personnel performing aquifer pumping tests shall record the applicable field data on Exhibit 6.2-1, Aquifer Test Data and shall sign and date the "measured by" and "date" blanks. Electronic datalogger printouts shall be stapled to the appropriate Exhibit for each monitor well. These personnel will also sign and date electronic datalogger printouts and all calculations prepared during aquifer pumping test analyses.

4.8 Review (continued)

The Site Manager or designee shall check Exhibit 6.2-1, Aquifer Test Data, electronic datalogger printouts and calculations prepared during aquifer test analyses for completeness and accuracy. Any discrepancies on these documents will be noted and returned to the originator for correction. The reviewer will signify that these review comments have been incorporated by signing and dating the applicable reviewed documents.

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6.0 EXHIBITS

Exhibit 6.2-1	Aquifer Test Data
Exhibit 6.2-2	Aquifer Testing Equipment List
Exhibit 6.2-3	Time Intervals for Drawdown Measurements in a Pumped Well
Exhibit 6.2-4	Time Intervals for Drawdown Measurements in Observation Wells
Exhibit 6.2-5	Pumping Test Discharge Rate Criteria

Page____ of _____

Exhibit 6.2-1
Aquifer Test Data

Owner ______________________ Address __________________________ County __________ State _______

Date ____________ Company performing test ____________________________ Measured by ______________

Well No. __________ Distance from pumping well ________ Type of test __________________ Test No. _________

Measuring equipment ____. Reviewed By: __________ Date: ______

Time Data	Water Level Data	Discharge Data	
Pump on: Date ______ Time ______ (t_0) Pump off: Date ______ Time ______ (t'_0) Duration of aquifer test: Pumping ______ Recovery ______	Static water level ______________ Measuring point ______________ Elevation of measuring point ________	How Q measured ______________ Depth of pump/air line ______________ Previous pumping? Yes ____ No ____ Duration ________ End ________	Comments on factors affecting test data

Date	Check Time	Time Since Pump Started t	Time Since Pump Stopped t'	t/t'		Water level measurement	Correction or Conversion	Water Level	Water Level Change s or s'		Discharge Measurement	Rate		

Exhibit 6.2-2 Aquifer Testing Equipment List

The following list represents field equipment necessary to successfully conduct a proper pump test:

Pickup truck with trailer hitch
Submersible pump and control box
Pump discharge pipe or hose (with quick connect fittings)
Manifold system with flowmeters (with quick connect fittings)
Discharge hose (with quick connect fittings)
5KW or 10KW generator with compatible AC plug system
Support boom with swing arm (to support pump in extraction well)
5 gallon fuel cans and funnel
Electric sounders (plus extra batteries)
Duct tape
Teflon tape
Work Gloves
Tools (especially pipe wrenches)
Tape measures (with increments in .01 ft)
Rinse bottle and extra D.I. water (prevents cross-contaminating wells)
Mirror
Flashlight
Stopwatch
5 gallon bucket
Rubber gloves
Pump test forms (Exhibit 6.2-1)
4 cycle semilog graph paper
Clipboard
Project site map, well logs, well detail sheets
Checklist
Keys to well locking devices
Pencils, rulers, calculator
Buckets with extra fittings, etc...(spare parts)
Appropriate safety equipment
Technical Operating Procedure 6.2 Aquifer Pumping Tests

Optional equipment may be required for the following reasons:

1. a long-duration test is required (24 hours or longer)
2. groundwater sampling is required
3. climatic conditions

Optional Equipment

Lantern with extra fuel
Raingear
Sampling equipment
Folding chair
Hat
Sun screen
Drinking water (many sites do not have this available)
1 inch PVC discharge line (as needed)
Toilet facilities

Exhibit 6.2-3 Time Intervals for Measuring Drawdown in a Pumped Well

Time Since Pumping Started (or Stopped) in minutes	Time Intervals Between Measurement in minutes
0 - 10	0.5 - 1
10 - 15	1
15 - 60	5
60 - 300	30
300 - 1440	60
1440 - termination of test	480 (8 hr)

Exhibit 6.2-4 Time Intervals for Measuring Drawdown in Observation Wells

Time Since Pumping Started (or Stopped) in minutes	Time Intervals Between Measurement in minutes
0 - 60	2
60 - 120	5
120 - 240	10
240 - 360	30
360 - 1440	60
1440 - termination of test	480 (8 hr)

MONITORING WELL NO:________

Exhibit 5.1-1

Monitor Well Sampling Data

Project:____________________ Job No: ____________________

Site No: ____________________ Sampling Time: ____________________

Location No: ____________________ Sampled By: ____________________

Sample No: ____________________ Reviewed by: ____________ Date:________

Sampling Date: ____________________ Elevation: ____________________

Sampling Method: ____________________ Weather ____________________

Bar. Pres.: ____________________ Amb. Temp. (°F) ____________________ °C

WATER ELEVATION DATA

1) Depth Water Surface________________ft
(from casing top as marked)

2) Static Water Level Elevation____________ft
(casing top elevation minus 1)

3) Depth to Well Bottom________________ft
(from casing top as marked)

4) Height of Water Column (h)____________ft
(4 minus 1)

Volume of Water in Well: (x) (h) = ____________gals
(for 2" x = 0.163 gal/ft fpr 4" x =0.653 gal/ft)

Amount of Water Removed from Well__________gals

Method of Water Removal____________________

Method of Measurement:________________

Products obs: ☐ Yes ☐ No

Depth to Product:________________

Method of Measurement:________________

Was Well Pumped Dry ☐ Yes ☐ No

WELL PURGE DATA

Method:____

Date:____________________ Total Volume/Time:____________________

Time	Temp °C	Conductivity	pH	Turbidity	Removed	Flow Rate	Observations

WATER SAMPLE DATA

Water Temp__________°C

Specific Conductance ____________micromhos Method of Measurement ____________

pH ____________________ Method of Measurement ____________

Containers Used (VOA Vial, 1 liter Jar etc.)____________________

Physical Appearance ____________________

Remarks ____________________

United States
Environmental Protection
Agency

Office of Environmental Processes and
Effects Research
Washington DC 20460

Research and Development

EPA/600/S8-86/004 Aug. 1986

EPA

Project Summary

EPA Ground-Water Research Programs

Brana Lobel

This document describes the U.S. Environmental Protection Agency's (EPA's) ground-water research programs. The programs focus on protection of ground-water resources by eliminating or controlling sources of contamination; understanding and predicting the movement and attenuation of contaminants in the subsurface; monitoring for contamination; restoring polluted aquifers; and ensuring that research findings are conveyed to public officials, field managers, and the scientific community.

This Project Summary was developed by EPA's Office of Environmental Processes and Effects Research, Washington, DC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Ground water is a vast and important resource. In the United States, approximately 15 quadrillion gallons (56 quadrillion liters) of water are stored within 0.5 miles (0.8 kilometers) of the land surface. Ground water supplies about 25 percent of all fresh water used. Fifty percent of U.S. citizens obtain all or part of their drinking water from ground water; and 95 percent of rural households depend totally upon it. Commercially, ground water is extensively employed in agricultural practices, particularly for irrigation, and in various industries.

Contaminants may leak, percolate, or be injected into aquifers. As contaminants travel through the soil and into a ground-water system, they may be slowed down or degraded by processes that are complex and not completely understood, but these natural processes are not totally effective for all contaminants. For example, soils were once believed to be capable of binding and holding all chemicals. This is now known to be false for some important and widely used classes of chemicals, like organic solvents such as tri- and tetrachloroethylene, benzenes, and carbon tetrachloride. Other contaminants such as heavy metals are not degradable at all but may be immobilized. Depending on the nature of the discharge and the type of pollutant, contaminants may enter ground water as slugs (isolated masses) or localized plumes.

ORD administers fourteen laboratories throughout the United States, four of which conduct research directly related to protecting ground water (Figure 1). Other ORD labs study drinking water quality, health effects, treatment technologies, analytical methods for water samples, and techniques for quality assurance. These investigations, which often address contaminants occurring in both surface and ground water, also provide valuable information and control tools.

In recent years, scientific knowledge about ground-water systems has been increasing rapidly. The ability to take uncontaminated samples in the subsurface—previously a major limitation in research—has been greatly improved. At ORD, researchers have developed techniques that allow them to enumerate and characterize subsurface microbes. ORD scientists have also stimulated the aerobic biodegradation of trichloroethylene (TCE). Improvements have been made in technology for assessing the subsurface, in adapting techniques from other disciplines to successfully identify specific contaminants in ground water, and in assessing the behavior of certain chemicals in some geologic materials. Each of these research areas is discussed in detail in the full report.

Source Control

Control of contaminant sources on the land surface represents both the beginning and end point of current ground-water research efforts. Until more is known about subsurface processes and their interactions with specific contaminants, source control remains the primary method for preventing ground-water contamination. At the same time, source control techniques are also used where contamination has already occurred, for example, in the cleanup of unregulated dump sites or in emergency response to accidental spills.

ORD supports two source control research programs through the Hazardous Waste Engineering Research Laboratory in Cincinnati, Ohio (HWERL-CIN). Both programs develop and evaluate state-of-the-art technology for hazardous waste management, storage, and disposal. The Hazardous Waste Land Disposal Program, in support of RCRA disposal regulations and guidelines, investigates landfills, surface impoundments, and underground storage facilities. The Removal and Remedial Action Program develops technology for emergency and ongoing hazardous waste site cleanup in support of CERCLA (Superfund). Table 1 lists current source control projects for both programs.

A major issue for almost all in situ treatment processes is to develop a means of employing them quickly and efficiently. As one answer, HWERL engineers and contractors are currently field-testing a prototype mobile in situ containment and treatment unit (ISCTU). This is a 45-foot-long (14-meter-long) drop-deck trailer capable of treating approximately 80,000 square feet (7,500 square meters) of contaminated soil approximately 25 feet (8 meters) deep per month. The system has the capacity to treat a variety of contaminants in several different soils.

The full report presents complete information on these other source control projects: Hazardous waste land disposal; landfill cover systems; clay soil and synthetic liners; waste modification; system evaluation; and insitu removal and remedial action.

Prediction

Predicting pollutant behavior in the subsurface is one of the most difficult—but also one of the most important—tasks for ground-water protection programs. Many interacting variables can influence the transport and fate of contaminants: for example, the source of contamination, the type of pollutants, climatic conditions, topography, and the geological and biological characteristics of the subsurface. The relative influences of various processes and conditions on the behavior of a contam-

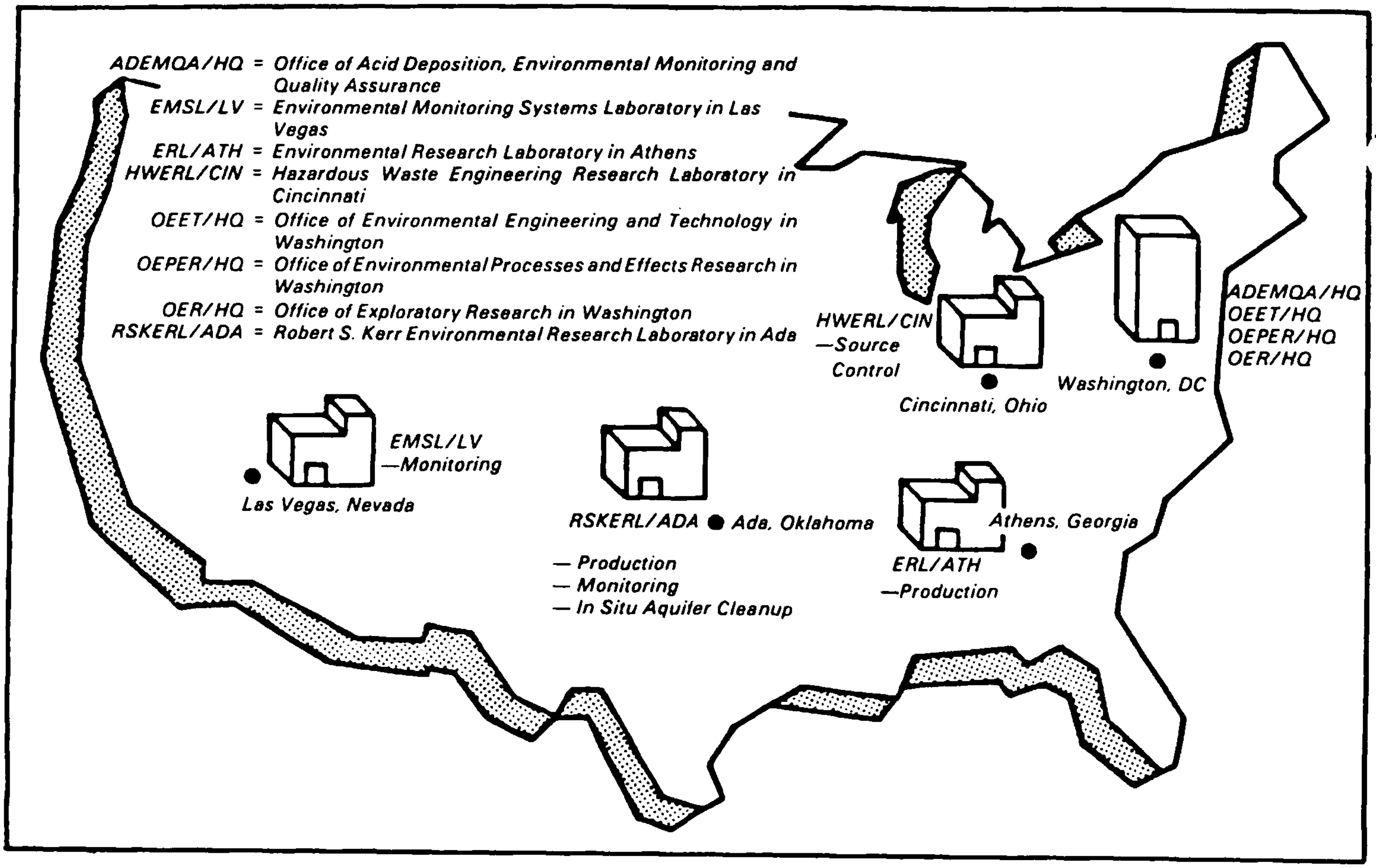

Figure 1. EPA offices and laboratories involved in ground-water research programs. All offices and laboratories shown here are part of the Office of Research and Development.

...nt can vary, dramatically affecting accuracy of predictions. Knowledge of these interactions must be refined in order to develop and improve mathematical models to predict chemical transport and fate. In order to gain this knowledge, continued research is needed to obtain representative samples, to develop more accurate laboratory simulations (microcosms) of environmental systems, to conduct field verification studies, to refine tools and procedures used to measure chemical and physical reactions, and to determine chemistry and biology in situ.

At EPA's Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma (RSKERL-ADA), researchers are investigating the movement of water in the ground (hydrogeology) and the various physical, chemical, and biological attenuation processes that degrade or destroy contaminants. In addition, RSKERL scientists and engineers are investigating methods for determining the mechanical integrity of injection wells and the interaction of injected fluids with geologic materials.

The Environmental Research Laboratory in Athens, Georgia (ERL-ATH) researches subsurface transport and transformation processes for organic pollutants and heavy metals, develops and tests leaching models for unsaturated zone transport to ground water, and provides technical assistance and methodology to support proposed RCRA regulations.

Table 2 summarizes current prediction research at RSKERL and ERL-ATH. The full report describes all key prediction projects listed in Table 2.

Monitoring

Monitoring provides information on

Table 1. *Source Control Research*
Hazardous Waste Engineering Research Laboratory—Cincinnati, OH

Area of Concern	*Project Title*	*Purpose*	*Goals and Products*
Land Disposal	*Office of Environmental Engineering and Technology (OEET)—Hazardous Waste—Surface Impoundments*	*Assess and develop improved design, operation, and closure components for landfills, surface impoundments, and waste piles used for hazardous waste management. Areas covered include gas and VOC (volatile organic chemical) emission control technologies, clay soil and FML (flexible membrane liner) liner performance, cover performance, contaminant/soil interaction, leachates, leak detection techniques, and dike construction criteria.*	• *Technical Resource Documents (TRDs)* • *Computer programs to review land disposal permit applications.* • *"Expert Information" computerized systems on containment technologies.* • *Technical assistance to RCRA permit writers.* • *Improved design and technology.*
... Disposal	*OEET—Hazardous Waste Technical Resource Documents*	*Develop and update technical manuals for landfilling and surface impoundment of hazardous wastes, including information such as design, construction, and operating and monitoring procedures. The manuals will address the design and installation of liners, the design of landfill covers to prevent infiltration, and closure procedures for surface impoundments.*	• *Provide state-of-the-art technical information to field managers and Federal, state, and local officials.*
Land Disposal	*Support to Land Disposal*	*Develop design, operation, maintenance, and closure procedures for landfills. Research topics include the effects of subsidence on cover performance, chemical compatibility and service life prediction for synthetic liners, leachate collection and treatment efficiency, cost effectiveness of multi-layer cover systems, assessment of maintenance-free cover systems, and the impact of designing secure landfills in saturated soils.*	• *Develop and improve the performance of components and the unit operations of secure landfills to comply with RCRA regulations.*
Remedial Action	*Chemical Treatment Methods for Dioxins and Dibenzofurans*	*Develop and evaluate methods for the destruction of dioxins and other chemically related wastes in soils, sediments, and contained waste streams. Laboratory and field studies will address the feasibility of UV photolysis and APFEG reagents for treatment of dioxin-contaminated soils, the removal of chlorinated dioxins from contaminated soils, the application of alkali polyethylene glycolate complexes to destroy dioxins in Missouri soils, and the supercritical extraction of chlorinated dioxins from soils.*	• *Improve chemical and physical contaminant destruction technology.*
Remedial Action	*Dioxin Assessment and Control Research*	*Evaluate the feasibility of incineration for on site detoxification of dioxin-contaminated liquid wastes and soils.*	• *Improve contamination destruction processes.*

Table 1. *(Continued)*

Area of Concern	Project Title	Purpose	Goals and Products
Remedial Action	*Engineering Support for Site and Situation Assessment*	*Apply engineering expertise to assessments of hazardous waste site situations (e.g., waste characteristics, hydrology, geology, and soil characteristics) to assist in developing corrective measures. Develop criteria for conducting site assessments. Prepare feasibility studies regarding data requirements for remedial action decisions.*	• *Technical assistance at hazardous waste sites.*
Remedial Action	*Provide Technical Support to Enforcement Program and Regional Offices*	*Provide scientific information and analyses in support of litigation on corrective actions at Superfund sites. Support areas include review of designs for remedial actions, review of data submitted by liable parties, expert witness testimony, technology transfer, emergency response assistance at releases and waste sites, supervision of cleanup operations involving ORD equipment, analytical support using mobile and central laboratories, and technical support regarding the designation of hazardous substances and assignment of reportable quantities.*	• *Technical assistance to EPA regional and state and local officials.*
Removal and Remedial Action	*Evaluate Technology to Manage Uncontrolled Waste Sites*	*Evaluate improved and new technologies for emergency and remedial actions for hazardous material spills and newly discovered releases of hazardous substances from uncontrolled waste sites. Topics include field evaluation of prototypical mobile equipment and innovative commercially available equipment, the use of chemicals for mitigation of the effects of hazardous substance releases, fugitive dust control procedures, and the fixation of contaminated soils.*	• *Provide most effective technology for spill control and release cleanup.*
Removal Action	*Prevent and Contain Hazardous Material Releases*	*Develop new and improved technology for the prevention and control of pollution from hazardous material releases by adapting related industrial technologies. Research topics include spill or accidental release prevention, preresponse planning, containment and confinement, separation and concentration, the destruction of collected cleanup residuals, and the selection of chemicals to control releases of floating hazardous substances.*	• *Improve technology for emergency handling of hazardous releases.*
Removal Action	*Special Biodegradation Processes for Detoxifying Contaminated Soils*	*Develop and evaluate biological methods for the destruction or detoxification of chemicals in soils. Genetic engineering and other biological techniques will be used to determine if living organisms such as plants, yeast, and microbes can be employed to successfully transform or degrade such substances as organochlorine compounds, 2,4,5-trichlorophenoxyacetic acid, chlorinated dioxins, and halogenated hydrocarbons.*	• *Cost-effective decontamination techniques.*

potential or known contamination. Many types of monitoring may be performed for a variety of reasons to determine probable contaminant pathways, to map actual contaminant flow, to locate sources of contamination, to identify contaminant plumes, and to detect leaching, percolation, or leaks. Monitoring research, conducted at the Environmental Monitoring Systems Laboratory in Las Vegas, Nevada (EMSL-LV), with assistance from the Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma (RSKERL-ADA), focuses on developing ground-water monitoring and sampling techniques and geophysical monitoring techniques, and refining methods for interpretive analysis of data. These techniques and methods are used to define the nature, location and movement of subsurface contami

Table 2. Ground-Water Prediction Research
Robert S. Kerr Environmental Research Laboratory—Ada, OK
Environmental Research Laboratory—Athens, GA

Area of Concern	Project Title	Purpose	Goals and Products
Biological Processes	Determination of Subsurface Microbial Activity	Adapt methods such as electron and epifluorescence microscopy and muramic acid assays to determine the abundance and metabolic activities of indigenous microflora in subsurface habitats. Develop methods to estimate the proportion of metabolically active bacteria to determine their nutritional state.	• Develop improved methods for identifying and characterizing subsurface microflora.
Biological Processes	Prediction of Microbial Contaminant Concentrations	Develop and evaluate predictive models describing the movement and survival of viruses and pathogenic bacteria in ground water.	• Provide methods and data for predicting chemical concentrations in ground water at a point of use.
Hydrogeologic Processes	Determination of Dispersion Coefficient Processes	Conduct field investigations to develop an understanding of physical and chemical components of dispersion.	• Determine the physical and chemical components of dispersion as used in solute transport models. • Increase applicability of prediction equations.
Management Aids	Determination of Waste Mobility by the Use of Microcosms	Evaluate soil profile and aquifer microcosms for their capacity to predict hazardous waste movement. Test protocols using selected chemicals from RCRA Section 3001. Compare results with field verification studies.	• Develop screening methods to assess hazardous waste exposure potential.
Management Aids	Enforcement and Other Technical Support	Provide consultation, project supervision, testimony, and analytical support for Superfund activities involving ground-water contamination.	• Provide technical support.
Management Aids	Evaluating Ground-Water Contamination Risks from Hazardous Waste Disposal	Investigate the processes that govern the transport rates, transformation, and fates of hazardous waste constituents in the subsurface. Evaluate mathematical models describing solute transport in the subsurface. Assess validity through field experiments.	• Provide field-evaluated methods and data to predict concentrations of contaminants from the treatment, storage, and disposal of hazardous wastes.
Management Aids	Methods to Determine the Impact of Geology on Ground-Water Quality	Develop techniques for determining the impact of geology, including the impact of surface development and water use, on ground-water quality. Develop methods for detecting geological areas within an aquifer that should not be developed for public water use because of naturally occurring contaminants such as chromium, selenium, uranium, and arsenic.	• Develop methods for determining impact of naturally occurring geological materials and conditions on ground-water quality.
Management Aids	Standard System for Evaluating Ground-Water Pollution Potential Using Hydrogeologic Settings	Develop a protocol to determine the pollution potential of any United States aquifer or area within an aquifer based on hydrogeologic criteria. Provide training and guidance in the use of the protocol.	• Provide technical basis for planning the location of land disposal sites. Preliminary system has been published, current field evaluations will lead to the development of the protocol.
Management Aids	Validation of Predictive Techniques for Environmental Exposure	Develop an extensive field data base to establish parameters to test exposure assessment models. These models are designed to assess pesticide migration through the saturated and unsaturated zones.	• Validate pesticide exposure assessment models, including PRZM, PESTANS, SESOIL, and SWAG.
Physical and Chemical Processes	Mathematical Models for Subsurface Transport and Fate	Create or modify a range of models for predicting concentrations of toxic chemicals in the subsurface.	• Provide a choice of mathematical models of contaminant transport and fate, suitable for a variety of computers, to aid in estimating exposure of humans, animals, and plant life.

Table 2. (Continued)

Area of Concern	*Project Title*	*Purpose*	*Goals and Products*
Physical and Chemical Processes	*Movement and Persistence of Dioxins in Soils and Ground Water*	*Determine batch sorption isotherms using labeled dioxins. Evaluate successive additions and extractions of dioxins to determine desorption characteristics and sorption kinetics in the subsurface. Validate transport potential using unsaturated microcosms.*	• *Provide capability to predict the rate of movement and transformation of dioxins in soils and ground water.* • *Assess potential for human exposure to dioxin.*
Physical, Chemical, and Biological Processes	*Prediction of Chemical Contaminant Concentrations*	*Examine sorption/retardation of organic contaminants in the subsurface in terms of subsurface characteristics and organic chemical properties. Define the subsurface microbial population and investigate capability to transform organic pollutants. Study abiotic transformations of organics and concentration effects on sorption and transport.*	• *Provide methods and data to predict concentrations of microbial contamination in ground water.*

nation. Table 3 lists current monitoring projects. The laboratories also provide operational guidance and technical support to EPA program and regional offices, and to state and local agencies. The full report describes each of the projects listed in Table 3.

In Situ Aquifer Cleanup

Restoring a polluted aquifer is generally an extremely expensive enterprise. Nevertheless, in some instances, restoration is the option of choice, for example, when there is no other local drinking water source, when the cost of transporting water from an alternative source equals or surpasses the cost of restoration, or when the damage to the aquifer has serious human health or ecological implications. The decision to attempt restoration of a polluted aquifer is rarely simple or clear-cut. Technical feasibility is only one aspect to consider and is often not the most pressing one. Economic, health, social, political, and other factors must be weighed against one another.

Until a range of inexpensive, effective cleanup methods is developed, managers who must decide whether to restore an aquifer face a series of difficult decisions. Serious thought, good management skills, and a solid information base are required. To meet these needs, researchers at RSKERL are concentrating on two approaches to improve existing cleanup methods: they are examining ways of making restoration techniques less expensive and more easily applicable, and they are examining case histories of restoration efforts to identify factors that influenced their success or failure. From this base, they are developing guidelines for decisionmaking. Table 4 summarizes current research projects at RSKERL. The full report describes several other key insitu aquifer cleanup projects.

Information Transfer and Technical Assistance

Transmitting information about current research to decision makers, field managers, and the scientific community is an important part of EPA's ground-water research programs. New research findings are communicated directly to the scientific, technical, and management community via information transfer mechanisms such as articles, documents, symposia, conferences, and training programs. In addition, ORD staff offer technical assistance to a variety of sources (for example, EPA regional and program offices, other federal and state agencies) to solve specific environmental problems.

The Robert S. Kerr Environmental Research Laboratory (RSKERL) conducts many information transfer activities and, in recent years, has provided technical assistance at over a dozen hazardous waste field sites in nine states.

At the Environmental Monitoring Systems Laboratory (EMSL), technical support investigations and training in geophysics are an important part of laboratory activities. Hazardous Waste Engineering Research Laboratory (HWERL) researchers provide scientific information and analysis in support of corrective actions at Superfund sites, as well as producing a series of technical handbooks on source control technology in support of CERCLA, and technical resource documents (TRDs) on specific areas of landfill design. HWERL has also recently established the Technical Information Exchange (TIX), a specialized reference center that provides state-of-the-art information on hazardous waste cleanup and emergency response technology. In addition to its technical support for the 1984 RCRA amendment land disposal banning rule, the Environmental Research Laboratory in Athens, Georgia (ERL-ATH) maintains the Center for Water Quality Modeling.

ORD also supports two centers that specialize in ground-water information transfer. The National Ground-Water Information Center (NGWIC) in Worthington, Ohio, houses the world's largest catalogued and retrievable collection of ground-water literature, concentrating on hydrogeology and water-well technology. It contains more than 10,000 volumes, including state publications, technical reports, government documents, maps, reference books, and related literature, plus over 120 periodical subscriptions. The NGWIC maintains its own computerized data base, with more than 35,000 references, and has the ability to search two international retrieval systems with access to over 150 additional data bases. The International Ground Water Modeling Center (IGWMC) serving North, Central, and South America, is located in Indianapolis, Indiana. The Center, supported largely by the EPA and in part by the Holcomb Research Institute at Butler University, operates a clearinghouse for more than 600 ground-water models, organizes and conducts short courses and seminars, and conducts a research program on ground-water modeling. A second IGWMC office in Delft, the Netherlands, not directly supported by EPA, serves Europe, Asia, Africa, and Australia.

Synergism in Research: the Stanford/Waterloo Project

Of necessity, ground-water re

Table 3. Ground-Water Monitoring Research
Environmental Monitoring Systems Laboratory—Las Vegas, NV
Robert S. Kerr Environmental Research Laboratory—Ada, OK

Area of Concern	Project Title	Purpose	Goals and Products
Monitoring and Sampling	Geophysical Surveys of Hazardous Waste Sites	Provide geophysical and geochemical monitoring support to EPA regional offices and EPA's Emergency Response Team for assessment of CERCLA hazardous waste sites.	• Meet RCRA land disposal regulations for ground-water detection and compliance monitoring for contaminants leaking from permitted facilities. • Provide cost-effective monitoring techniques. • Support remedial and removal actions at CERCLA sites. • Establish standard procedures for the application of geophysical and geochemical techniques. • Conduct geophysical surveys on request.
Monitoring and Sampling	Ground-Water Quality Protection from Injection Wells	Test the mechanical integrity of injection wells. Develop an overview of contamination cases associated with Class II and V injection wells.	• Provide technical support in the implementation of Underground Injection Control (UIC) regulations.
Monitoring and Sampling	Methods for Monitoring Well Construction	Assess alternative methods for constructing monitoring wells to determine problems with surface and subsurfce contamination; select and field-test recommended monitoring options.	• Determine and recommend preferred well drilling and sealing techniques to derive accurate ground-water samples.
Monitoring and Sampling	Monitoring Ground Water with Fiber Optics Technology	Evaluate the feasibility of performing contaminant-specific ground-water monitoring using fiber optics technology combined with laser fluorescence spectroscopy.	• Develop methodology and hardware to monitor organic and inorganic chloride concentrations. • Conduct field demonstration to identify weaknesses in the methodology. • Improve response time and lower cost of monitoring technology.
Monitoring and Sampling	Unsaturated Zone Monitoring for Hazardous Waste Sites	Evaluate agricultural equipment and methods for monitoring in the vadose zone to detect leaching and percolation of pollutants from hazardous wastes. Determine the relative effectiveness of suction and gravity lysimeters.	• Adapt existing technology to meet RCRA regulations for monitoring at permitted land treatment or land farming disposal areas. • Provide guidance for lysimeter performance for permit writers. • Develop technical resource document on unsaturated zone monitoring at hazardous waste land treatment units.
Monitoring and Sampling	Well Construction and Sampling for Ground-water Quality Analyses	Develop methods for constructing, completing, and sampling ground-water monitoring wells to obtain representative physical, chemical, and biological data.	• Update manual for sampling ground-water quality parameters
Geophysics	Detection of Leachate Plumes in Ground Water with Geophysics	Evaluate geophysical and geochemical methods to detect and map organic and inorganic leachate plumes at hazardous waste sites, emphasizing soil-gas sampling techniques for mapping organic plumes.	• Establish guidelines for the number of sample points required to map a plume. • Develop quality assurance guidelines for the calibration of equipment and procedures for mapping hazardous waste sites.

Table 3. (Continued)

Area of Concern	Project Title	Purpose	Goals and Products
			• Provide guidance on the application of geophysical and geochemical techniques to hazardous waste sites. • Recommend procedures for hazardous waste site investigations.
Geophysics	Downhole Sensing for Hazardous Waste Site Monitoring	Design, build, modify, and evaluate sensing devices and methods used to obtain geohydrologic data from monitoring wells.	• Develop new technology or modify existing technology for typical small-diameter, shallow-depth, plastic-cased monitoring wells. • Develop procedural manual for use by site operators and regulatory personnel. • Make conference presentations on project efforts.
Geophysics	Geophysical Sensing of Fluid Movement from Injection Wells	Map the migration of wastes from injection wells at depths of 1,000+ feet at several field sites, using the time-domain electromagnetic method.	• Assess the applicability of time-domain EM technology to meet Underground Injection Control (UIC) regulation requirements. • Develop a technical transfer report.
Interpretive Analysis	Locating Abandoned Wells with Historical Photographs	Identify abandoned oil and gas wells through historical aerial photographs and verify by comparison with conventional records.	• Assist EPA regional officials in examining large areas for abandoned gas and oil wells to comply with UIC regulations. • Provide reports with area maps indicating photo-identified oil and gas well locations.
Interpretive Analysis	Indicator Methods for Ground-Water Detection Monitoring	Determine parameters that indicate the presence of hazardous constituents in ground water at land disposal sites, using existing data from Consent Decree, Super-fund, and RCRA site monitoring files.	• Evaluate performance of selected indicator parameters. • Meet RCRA requirements for detection and compliance monitoring as part of land disposal ground-water monitoring programs. • Identify "missed classes" of hazardous constituents. • Develop a short list of parameters that are (1) reliable indicators of leakage, and (2) inexpensive to measure.

searchers often examine discrete subject areas (for instance, dispersion in certain immiscible fluids), and study them on a small scale (for instance, in a laboratory microcosm). Because ground water is a complex subject, this is often the best way to gain a clearer comprehension of individual processes. However, researchers must consider whether the results of short-term, discrete, small-scale studies will validly translate to the long-term realities of contaminant movement in ground water. The question arises: How to take the small pieces of the puzzle and fit them into a larger, coherent whole?

In one effort to address this question, ORD has sponsored the Stanford/Waterloo project, an attempt to provide new understanding of the long-term behavior of contaminants in ground water. This project is an extramural effort monitored by the RSKERL laboratory and conducted jointly by Stanford University and the University of Waterloo, Ontario, Canada. It has two components: a large-scale study of organic contaminant transport, and an investigation of leachate from municipal sanitary landfills. Each of these studies is described in detail in the full report.

Future Directions

Ground water presents a series of complex issues for study. Our industrial society, with its plethora of chemicals and by-products, combined with our diverse topography, geohydrology, and climate, create an intricate matrix fo

Table 4. *In Situ Aquifer Cleanup Research*
Robert S. Kerr Environmental Research Laboratory—Ada, OK

Area of Concern	Project Title	Purpose	Goals and Products
Case History/Cost-Benefit Analysis	*Methods for Protecting Public Water Supplies from Existing Ground-Water Contamination*	*Determine cost-effectiveness and feasibility of alternate aquifer cleanup methods by examining social, political, institutional, and technical issues in case studies.*	• *Provide states and localities with methods of assessing technology to protect public water supplies.*
Case History/Cost-Benefit Analysis	*Analysis of Cost-Effectiveness of Aquifer Restoration Techniques*	*Evaluate incremental benefits versus incremental costs of cleaning up a range of waste sites, considering political, social, economic, and medical issues, as well as cleanup effectiveness.*	• *Determine the effectiveness of various aquifer restoration techniques.* • *Develop hierarchical decision-making set to determine "how clean is clean?"*
Technology	*Feasibility of Enhancing the In Situ Biodegradation of Contaminants in Ground Water*	*Detect the presence of plasmid DNA in ground-water bacteria and evaluate the ability of ground-water bacteria to act as hosts for specific plasmid DNA associated with biodegradation. Evaluate the behavior of the plasmids in subsurface material.*	• *Evaluate the feasibility of enhancing in situ biological degradation of ground-water contaminants.*
Technology	*Laboratory and Field Evaluation of Methodology for In Situ Aquifer Restoration*	*Evaluate selected cleanup methods, including physical removal, chemical treatment, and enhanced biodegradation for feasibility and cost-effectiveness.*	• *Develop cleanup protocols using the results of the project.* • *Develop the process for aerobic degradation of TCE (trichloroethylene) for use in the field.*
Technology	*Simulated Aquifer Restoration*	*Test aquifer restoration methods under simulated conditions by creating an artificial aquifer that can be mathematically represented.*	• *Use artificial aquifer systems to develop aquifer restoration methods.*
[illegible]iology	*Monitoring the Development of Active Subsurface Organisms During Bioreclamation of Polluted Aquifers*	*Evaluate existing methods for determining the population sizes of bacterial groups that may be used to biodegrade contaminants in aquifers.*	• *Increase scientific information that will lead to effective bioreclamation techniques.*

contamination scenarios. Physical and chemical theories must be modified to apply to variable and often inaccessible conditions in the subsurface. The relative newness of ground-water investigation, combined with its complexity, point to several basic research priorities:

- Identify and study major existing and potential contamination sources and agents.
- Invent and/or refine effective, inexpensive technology for monitoring and sampling, source control, and basic predictive research.
- Develop reliable mathematical models to predict the movement and transformation of contaminants in ground water.
- Provide ground-water training for EPA, state, and local officials.
- Transmit information quickly. The time lag between the verification of research findings and practical application should be made as narrow as possible.

To supplement these recommendations, Appendix A of the full report presents the principal findings and recommendations by the Ground-Water Research Review Committee of EPA's Science Advisory Board. The committee's recommendation covers staffing, the Superfund, accelerated research, technology and training.

Ground-Water Research in Other Federal Agencies

Several Federal agencies sponsor research programs that examine ground-water-related issues. The descriptions of their research given in the full report are not intended to be comprehensive but rather to provide a general context in which to place EPA's research programs. For more detailed information, the reader should contact the specific agencies mentioned.

The ground-water research of other Federal agencies is summarized in Table 5. EPA integrates its research efforts with these other agencies through joint projects, work groups, committee participation, and informal information exchange. The United States Geological Survey (USGS) is the major Federal agency doing ground-water research, and receives the bulk of Federal funding. Since 1981, EPA has operated under a general memorandum of understanding (MOU) with the USGS. As a result of EPS's Ground-Water Protection Strategy (of which the research program are a part), an MOU specifically on ground water was signed in June 1985. It addresses data collection and technical assistance as well as research coordination. Appendix B of the full report describes in detail the research programs listed in Table 5.

Table 5. *Ground-Water Research In Other Federal Agencies*

Agency	Research Category: Source Control	Prediction	Monitoring	Cleanup	Objective
U.S. Air Force	•	•	•	•	Develop methods for predicting the impact of Air Force activities on ground water.
U.S. Army Corps of Engineers	•			•	Develop cost-effective ground-water pollution control and monitoring systems; provide environmental and health effects data on Army-unique pollutants; develop environmental management systems and data bases.
U.S. Department of Agriculture	•	•	•		Provide basis for evaluating effects of changes in agricultural techniques on ground-water quality.
U.S. Department of Energy	•	•	•		Provide information on mechanisms contributing to transport and long-term fate of energy-related contaminants in ground water.
U.S. Geological Survey		•	•		Provide research to describe, assess, and develop ground-water resources.
National Science Foundation[1]	•	•	•	•	Perform basic research.
U.S. Navy[2]					
Tennessee Valley Authority	•	•	•		Provide data needed for assessing the significance of potential Tennessee Valley ground-water contamination sources and for preventing and isolating contamination.

[1]Fundamental researach will contribute to all areas, although it is not necessarily specifically directed toward ground-water projection.
[2]Program just beginning to be defined.

The EPA author **Brana Lobel** is with the Office of Environmental Processes and Effects Research, Washington, DC 20460.

The complete report, entitled "EPA Ground-Water Research Programs," (Order No. PB 86-212 552/AS; Cost: $9.95, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA author can be contacted at:
Office of Environmental Processes and Effects Research
U.S. Environmental Protection Agency
Washington, DC 20460

United States
Environmental Protection
Agency

Research and Development

Environmental Monitoring
Systems Laboratory
Las Vegas NV 89193-3478

EPA/600/S4-89/032 Sept. 1989

EPA

Project Summary

Sampling Frequency for Ground-Water Quality Monitoring

Michael J. Barcelona, H. Allen Wehrmann, Michael R. Schock, Mark E. Sievers, and Joseph R. Karny

This project was initiated to collect a benchmark water-quality dataset end evaluate methods to optimize sampling frequency as a network design variable. Ground water was collected biweekly for 18 months from twelve wells at two sites in a shallow sand and gravel aquifer in Illinois. Sampling and analyses were conducted for twenty-six water quality and geochemical constituents with careful quality control measures to allow statistical analysis of variability in ground-water quality data. The results demonstrate that natural variability over time can exceed the variability introduced into the data from sampling and analysis procedures.

Natural temporal variability and the highly autocorrelated nature of ground-water quality data seriously complicate the selection of optimal 8ampling frequency and the identification of seasonal trends in ground-water quality variables. Quarterly sampling frequency is a good initial starting point for ground-water quality monitoring network design, although bimonthly frequency may be preferred for reactive chemical constituents. Analysis of data collected during this project suggests that the collection of a long-term (i.e., more than two years) dataset is necessary to determine optimal sampling frequency and to identify seasonal trends in ground-water monitoring results.

This Project Summary was developed by EPA's Environmental Monitoring Systems Laboratory, Las Vegas, NV, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

There are two principal sources of variability in ground-water quality data. "natural" variability and variability resultant from the network design and operation The components of "natural" variability arise from temporal or spatial variability related to hydrologic processes such as pumpage, recharge or discharge, as well as influences of these processes on the release and distribution of chemical constituents from a variety of chemical sources. The sources may be natural mineral assemblages, precipitation and percolation through the unsaturated zone, in addition to numerous point and non-point sources of chemical contaminants. In general, "natural" sources of variability cannot be controlled although they may be quantified through effective monitoring network design.

Water-quality data variability may also arise from the sampling and analytical components of monitoring network design. Sampling variability includes variations due to the selection of the locations and construction of sampling points in space, sampling frequency, well purging, and the execution of the sampling protocol. The sampling protocol consists of the procedures used to collect, handle, preserve, and transport water samples to the analytical laboratory. Elements of the sampling protocol have been evaluated for their relative contributions to variability or errors in water-quality data in previous research.

Analytical variability in water-quality data arises principally from the errors involved in analytical methods and the subsequent data processing steps. These errors can be controlled once suitable water-quality indicators or chemical constituents have been selected and a thorough data quality assurance/quality control program has been designed and executed.

This study was planned to control the sources of variability in water quality data which result from network design components such as sampling location, frequency, sampling methods and analytical procedures. The sampling frequency was held constant at a biweekly interval between sample collection dates. The benchmark dataset that resulted from this experimental design could then be analyzed to determine the optimal sampling frequency for selected water-quality variables at both uncontaminated and contaminated study sites.

The full report describes the level of QA/QC effort which is necessary to achieve control over sources of error and data variability due to sampling and analytical operations. Discussions of temporal variability in groundwater level and water quality results are included in the report to place the dataset in perspective. The results and conclusions of the work are supported by extensive references, where the literature permits. The report should be useful to the planning and execution of regulatory and research activities which demand the cost-effective collection of high quality ground-water quality data.

Variability in Ground-Water Quality

The impact of the sources of variability mentioned above will be influenced by the hydrology of the ground-water system. It is important to understand that although aquifer hydraulic properties may not vary significantly at a single measurement point over time, spatial variability may be substantial. Aquifer hydraulics may be expected to influence chemical constituent distributions in space and time.

Temporal and spatial variations in ground-water elevation may affect ground-water flow rate and the direction of movement. Such changes may influence the quality of the ground water in the vicinity of a sampled well by directing water from a different upgradient area or changing the velocity with which dissolved constituents move along a flow path. Examples abound in the literature detailing ground-water response (i.e., elevation change) to a wide variety of influences. In addition to seasonal fluctuations produced in response to short-term (i.e., months to one year) events, ground-water levels also reflect changes in long-term (i.e., years to decades) conditions.

Temporal and spatial variability may also result from sample collection and measurement errors inherent to network design and operation. This variability, or "noise," in the data embodies the stochastic distribution of possible values for particular chemical constituents and the effects of both determinate (i.e., systematic) and indeterminate (i.e., random) error. Determinate error can be measured as inaccuracy or bias if the "true value" is known. Indeterminate error can be estimated as imprecision or irreproducibility if a sufficient number of replicate determinations can be made to faithfully estimate the mean or the "true" value.

Statistical measures of short-term temporal variability include seasonal effects (e.g., consequences of recharge or temperature effects) which can be assigned to the seasons of the year, periodic effects (e.g., consequences of anthropogenic contaminant sources or pumping effects) and serial correlation or dependence effects which tend to make data points following maxima or minima in temporal data series higher or lower, respectively, than one would attribute to random processes alone. Trends in data, on the other hand, are long-term variations compared to those which may occur within a hydrologic year.

Procedure

Field Sites

Two sites were chosen to enable the isolation of the effects of network design variables fro those due to natural or contaminant-related sources. The sites were located over an alluvial sand and gravel water table aquifer of moderate to high yield. One site was in a pristine environment far removed from any sources of contamination in the Sand Ridge State Forest near Havana, Illinois. The other site was in an industrial environment under the influence of a leaking anaerobic waste impoundment near Beardstown, Illinois.

Sand Ridge State Forest is an Illinois Department of Conservation (IDOC) facility located 5 miles (8 km) southeast of the Illinois River in the north-central Havana Lowland. The Illinois State Water Survey's experimental field site is loc in the middle of the State Forest . Havana, Illinois.

Three distinct horizons comprise the unconsolidated deposits at Sand Ridge: at the surface is 30 feet (9 m) of dune sand (the Parkland sand); from 3D feet (9 m) to a depth of 55 feet (17 m) is the Manito Terrace of the Wisconsinan outwash, consisting of a sometimes silty, sometimes coarse sand to medium gravel; and from 55 feet (17 m) down to bedrock below 110 feet (34 m), and possibly as deep as 150 feet (46 m), is the medium sand to fine gravel of the Sankoty sand (Kansan outwash).

Depth to the water table is greater than 30 feet (9 m) below the ground surface. Ground-water movement is generally toward the Illinois River. The hydraulic gradient measured at the site in 1983 was approximately 0.0016. Aquifer tests conducted on the water supply wells at a nearby state fish hatchery indicate that the hydraulic conductivity of the sand and gravel at approximately 100 feet (30 m) depth (in the Sankoty sand) is about 2000 gpd/ft^2 (0.094 cm/sec). Tracer experiments conducted in 1983 indicated that 1over hydraulic conductivities (from 250 to 1900 gpd/ft^2, 0.01 to 0.09 cm/sec) may be exhibited by the finer-grained, : lower materials. Hydraulic conducti , values of 350 to 900 gpd/ft2 (0.02 to 0.04 cm/sec) were obtained by empir methods of analysis based on the grain size distributions of shallow aquifer samples. The porosity of the saturated terrace materials was found to be 25%.

The "contaminated" field site is located in the vicinity of several liquid waste impoundments serving a pork slaughtering facility approximately 1 mile (1.6 km) southeast of Beardstown, Illinois. The field site lies two miles southeast of the river, and it is only about 5 feet (1.5 m) higher than the floodplain. Farmland and wooded areas surround the facility. The unconsolidated deposits lying above the bedrock consist of the clayey sands of the Beardstown Terrace on the Wisconsinan outwash plain. The bedrock surface is of Mississipian age and lies at about 100 feet (30 m) below the ground surface.

Owing to land surface elevation changes, depth to water varies from 5 to 15 feet (1.5 to 4.5 m) below the ground surface. Similar to the Sand Ridge site, regional ground-water flow is toward the Illinois River (hydraulic gradient, 0.002). Due to the presence of silt and clay, aquifer is less permeable than it is a

Sand Ridge site. One falling head permeability test produced a hydraulic conductivity value of only 130 gpd/ft^2 (6 x 10^{-3} cm/sec).

Monitoring Wells

Bore holes for construction of all monitoring wells were drilled with a 4.25-inch (11 cm) inside diameter (I.D.) hollow-stem auger. All auger flights, solid samplers, well casing materials, and well protectors were steam cleaned before use or placement in the bore hole.

The construction details of the sampling wells at both sites are identical in all ways other than the length of casing and casing materials in two wells at Beardstown. One well at Beardstown vas constructed of stainless steel (SS) and one other of polyvinylchloride (PVC). All of the other sampling wells at both sites were constructed with polytetrafluoroethylene (PTFE-Teflon®, DuPont). All wells have 2-inch (5 cm) I.D. flush-threaded casing. Screens were 5 feet (1.5 m) long with 0.01-inch (0.02 cm) slot openings. The four wells at Sand Ridge were completed at depths of 35, 50, 65, and 105 feet (10.6, 15.4, 20, and 32 m), respectively.

The eight wells at Beardstown were completed at several depths at locations upgradient and downgradient from the impoundment.

Results and Discussion

Five preliminary sampling runs were completed between November 1985 and March 1986. Then thirty-nine biweekly sampling trips were conducted during the period of March 10, 1986 through August 25, 1987. These field activities involved purging and sampling the monitoring wells 526 times and measuring more than 2,000 ground-water levels. Only two wells were missed out of the 528 sampling opportunities. Water samples were collected for more than 26 analytical determinations each, including major cations, anions, TOC; TOX, pH, alkalinity, and other species.

During the course of the study, more than 55,000 analytical determinations vere made on blanks, standards and samples. The final dataset was 96% complete, that is, 96% of the maximum possible number of samples and subsequent analytical determinations were successfully completed. Outliers were screened successively at ±3 and ±2 standard deviations from the mean levels. In most cases, this screening revealed apparent errors in calculations, calibration or data entry which were corrected prior to data analysis. For all wells and constituents, the maximum number of samples which were identified as possible outliers and for which no documented error was identified was four percent of the total. No adjustment was made to apparent outliers for which no documented error could be identified. QA/QC analyses demonstrated that the analytical methods were within control limits and that good analytical performance was maintained throughout the project period.

Estimation of Sources of Variation

Generally, the natural variations in water quality time series are of interest. For instance, the difference between the time series of a given contaminant at a downgradient and an upgradient well may give an indication of whether contaminant release has occurred. However, the difference series is inevitably corrupted by errors in the field data collection and laboratory analysis procedures, both of which introduce what may be considered "noise" into the time series. Each of these noise processes has a variance, and the total variance is the sum of the three variance terms. this model assumes that the three sources of variation are statistically independent. This is a reasonable assumption because the sources are physically independent and the individual variances were calculated from the analytical results from replicate control samples, lab and field spiked samples.

The results are summarized in Table 1 for three groups of wells (i.e., Sand Ridge wells 1 to 4, Beardstown upgradient wells 5 and 6, and the Beardstown downgradient wells). for almost all of the groups, and for almost all of the chemical constituents, a high fraction of the total variation was natural. In most cases the combined lab and field variances were below ten percent of the total variance. This is consistent with the QA/QC data analyses, which showed that the data collection errors were generally quite small. The entries in the table have been separated into water quality parameters and chemical parameters of geochemical interest. The results confirm that if careful sampling and analytical protocols are used, the analytical and sampling errors can be held to less than about 20%. Therefore, the natural variability in the major ion chemistry of the system can be identified. For TOC and TOX it is clear that "natural" sources of variability are greater than the combined lab and field variance. However, the level of overall variability in TOX results was quite large in comparison to the mean values for each well. The significance of these determinations at the microgram per liter concentration level is doubtful.

The implication of the results of this study is that network design optimization efforts should focus primarily on the natural or contamination source-related variability. The use of field and laboratory replication for purposes other than QA/QC will be difficult to justify as long as the sampling and analytical protocols are in control. This conclusion must be qualified, however. The chemical constituents present at appreciable concentrations (i.e., mg·L-1) at either site were the major cations and anions and general water quality indicators. The analytical and sampling variances for trace organic contaminants would be expected to be higher, and their analytical recoveries are frequently found to be a function of concentration. For such contaminants, the field and laboratory variations may not be independent, which would violate a basic assumption in this model.

Temporal Variations in Ground-Water Quality

There are numerous examples of both short- and long-term variability in ground-water quality in the literature. Significant short-term temporal concentration variability has been observed in low-yield wells (i.e., monitoring and observation wells) largely resulting from purging effects. Similar variations from one to ten times the initial or background concentrations have been noted in samples from high-volume production wells due to pumping rate, initial pumping after periods of inactivity, and cone of depression development.

In general, the major ionic chemical constituents determined in this study showed differences between their overall maximum and minimum values from the mean for each well on the order of one or two times the mean value. One or two times the mean value places the variability noted in this study in the same range as long-term, seasonal variability. The magnitude of overall long-term variations observed in this study and the literature is often much lower than those noted for short-term variations due to pumping and local recharge effects. The magnitude of short-term concentration variations noted in the literature strongly suggests that the analysis of ambient resource, water quality datasets must be undertaken with careful attention to the

Table 1. Percentage of Variance Attributable to Laboratory Error, Field Error, and Natural Variability by Chemical and Site

Type of Parameter	Sand Ridge			Beardstown (Upgradient)			Beardstown (Downgradient)		
	Lab	Field	Nat	Lab	Field	Nat	Lab	Field	Nat
<u>Water Quality</u>									
NO_3^-	0.0	0.0	100.0	0.1	NA*	99.9	0.2	NA	99.8
$SO_4^=$	0.0	0.0	100.0	0.2	NA	99.8	1.4	0.0	98.6
SiO_2**	0.0	NA	100.0	0.0	20.0	80.0	0.0	6.8	93.2
$o\text{-}PO_4$**	1.2	1.2	97.6	0.0	0.0	100.0	0.0	0.0	100.0
$T\text{-}PO_4$	0.0	NA	100.0	2.8	NA	97.2	0.9	NA	99.1
Cl^-	7.2	NA	92.8	0.0	3.3	96.7	0.0	17.2	82.8
Ca	0.0	45.7	54.3	0.0	2.3	97.7	0.0	3.6	96.4
Mg	0.0	20.0	80.0	0.0	2.2	97.8	0.0	2.8	97.2
Na	0.0	NA	100.0	0.0	0.3	99.7	0.0	7.1	92.9
K	0.0	NA	100.0	33.9	NA	66.1	87.1	NA	12.9
<u>Geochemical</u>									
NH_3	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0	100.0
NO_2	NA	NA	NA	0.1	NA	99.9	0.3	NA	99.7
$S^=$	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fe^{2+}	NA	NA	NA	0.0	0.1	99.9	0.0	5.9	94.1
Fe_T	0.0	NA	100.0	0.0	0.0	100.0	0.0	NA	100.0
Mn_T	0.0	NA	100.0	0.0	40.1	59.9	0.0	73.6	26.4
<u>Contaminant Indicator</u>	<u>Lab + Field</u>			<u>Lab + Field</u>			<u>Lab + Field</u>		
TOC**	15.4		84.6	29.9		70.1	40.5		59.5
TOX**	0.0		100.0	12.5		87.5	24.6		75.4

*NA indicates that the number of observations on which the estimated variance was based was less than 5, or the estimated variance was negative.

**True field spiked standards not available for these constituents, demanding combined estimates of laboratory and field variability.

pumping procedures used in purging and sample collection. This observation is particularly critical in relatively sparse datasets where annual "mean" concentrations may be determined from programs with low sampling frequency (i.e., annually, biannually, etc.). Similar cautions in interpretations of long-term datasets apply in the analysis of trends at varying or unequal sampling frequencies due to the relatively short duration of the records in comparison to the length of apparent annual to multi-year variations.

Sampling Frequency

The primary purpose of the project was to investigate the optimal sampling frequency for ground-water quality monitoring. Strictly speaking, there is no minimum sampling frequency. However, there is a relationship between the information content of the data and the sampling frequency. The term "information" is sometimes used loosely, but in a statistical context, it can be given a more precise definition, depending on the use of the data. The most common definition of information (e.g., in the Fisher sense) is in terms of the variance of the mean, $Var(x) = \sigma^2/n$, where x is the sample mean, n is the sample size, and σ^2 is the variance of the data. The reciprocal of the variance of the mean is a measure of the information content of the data. If the σ^2 is large, or the sample size small, the information content is low. While this definition of information applies to estimation of the mean, the power of trend detection (in space or time) is related to the variance of the mean as well.

Seemingly, the information content of the data could be increased arbitrarily, since it depends linearly on the sample size. In practice, though, ground-water quality data are correlated in time (autocorrelated), and the autocorrelation increases with the sampling frequency. When the data are autocorrelated, the variance of the mean can be reexpressed as $Var(x) = \sigma 2/n_{ef}$, is an effective independent sample size, which depends on the autocorrelation. The value of n_{ef} is always less than n, the actual sample size, if the autocorrelation is positive, as it usually is in practice. If the model that describes the autocorrelation is the lag-one Markov process, n_{ef} approaches an upper limit as the sampling frequency increases, regardless of how large n becomes. The lag-one process has been found to provide a reasonable description of many water quality time series. It is often difficult to extend the analysis of water quality data beyond lag-one because the autocorrelation function becomes excessively noisy.

The ratio n_{ef}/n can be considered to be a measure of the loss of information due to autocorrelation in the data. Although n_{ef} always increases with n for positive autocorrelation, n_{ef} may increase quite slowly if the autocorrelation is high. For this reason, one of the analyses conducted was to estimate a model of the serial dependence (i.e., autocorrelation) in the observed chemical series.

To illustrate the effect of the autocorrelation on sampling frequency, we solved for the sampling interval, in weeks, that would result in ratios n_{ef}/n = 0.5, 0.8, and 0.9. Alternatively, these can be interpreted as relative losses of informat[illegible] due to autocorrelation in the data of [illegible]

20, and 10 percent. The results are given in Table 2. At Sand Ridge, the implied loss of information was about 50 percent for many variables at a weekly sampling frequency, 20 percent for many variables at sampling intervals in the range of 4-8 weeks, and 10 percent for the majority of variables at a sampling interval of 8 weeks or more.At the Beardstown wells, the loss of information at high sampling frequencies was much greater. At the upgradient wells, which had the highest autocorrelation, the inferred loss of information of 50 percent occurred for several variables at a sampling interval of over 26 weeks. Information loss of between 20 and 10 percent was inferred for some variables at sampling intervals exceeding one year. This effect was particularly evident for Na^+, Cl^- and well-head temperature (TEMPW) which showed an increasing trend over the study period.

The results of the study indicate that, for the major chemical constituents (i.e., water quality or contaminant indicator), quarterly sampling represents a good starting point for a preliminary network design. Some estimated ranges of sampling frequency to maintain information losses below ten percent are shown in Table 3. This frequency, of course, must be evaluated with respect to the purpose and time-frame of which the network will be conducted. For the conditions of this study, sampling four to six times per year would provide an estimated information loss below 20% and minimize redundancy. The results for reactive, geochemical constituents suggest that bimonthly sampling frequency would be a good starting point if chemical reactivity and transformation are of concern.

Caution must be exercised in interpretation of these results due to the effects of seasonality and long-term trends. However, it should be clear that there is considerable redundancy in the data at the two-week sampling interval, and that, at similar sites and for most of the variables studied, operational sampling programs would be inefficient at sampling intervals more frequent than bimonthly.

It is important to emphasize that the information from sampling depends on the effective independent sample size, not just the ratio n_{ef}/n. Therefore, if the autocorrelation is large so that a relatively low sampling frequency is necessary to avoid sampling redundancy, the total length of the sampling period must be increased to achieve sufficient information return. These results cannot simply be interpreted to mean, for instance, that quarterly sampling is adequate, unless that interpretation is couched in terms ofthe time horizon of the sampling program.

Table 2. Sampling Intervals (in Weeks) for Given Ratio of Effective to Independent Sample Size, Based on the Estimated Lag One Markov Model

	n_{ef}/n 0.5	0.8	0.9
<u>Sand Ridge</u>			
NO_{2+}·N	2	4	5
Fe	1	1	2
pH	4	7	9
S^-	2	3	4
NH_3	2	4	5
SiO_2	3	5	6
Mn_T	4	7	9
Probe O_2	3	5	7
t-$PO_4^{\equiv}$	1	2	3
O-$PO_4^{\equiv}$	1	2	3
Eh	3	6	8
NO_3NO_2-N	8	16	21
TOC	3	6	8
$SO_4^{=}$	5	9	12
Fe_T	2	3	4
K	2	4	5
Ca	3	6	8
Mg	4	7	9
Cl^-	2	3	4
Na	3	6	8
Alk	7	14	19
Ion Balance	7	14	19
Temp Cell	4	8	10
VOC	4	8	10
Cond	10	10	27
TOX	10	20	27
Temp Well	6	11	15
NVOC	6	11	15
<u>Beardstown Upgradient</u>			
NO_{2+}·N	3	6	7
Fe	15	29	39
pH	3	6	8
S^-	3	5	6
NH_3	11	22	30
SiO_2	8	16	22
Mn_T	3	6	8
Probe O_2	6	11	15
t-$PO_4^{\equiv}$	2	3	4
O-$PO_4^{\equiv}$	2	3	4
Eh	5	9	12
NO_3NO_2-N	3	5	6
TOC	5	9	12
$SO_4^{=}$	4	7	10
Fe_T	21	42	56
K	19	38	51
Ca	26	53	71
Mg	23	47	62
Cl^-	53	107	144
Na	42	85	114
Alk	6	12	16
Ion Balance	6	12	16
Temp Cell	26	53	71
VOC	26	53	71
Cond	35	71	95
TOX	35	71	95
Temp Well	71	143	192
NVOC	71	143	192

Table 2. (continued)

		n_{ef}/n	
	0.5	0.8	0.9
Beardstown Downgradient			
NO_{2+}- N	3	5	6
Fe	4	8	11
pH	2	3	4
S-	6	11	15
NH_3	2	4	5
SiO_2	2	4	5
Mn_T	2	3	4
Probe O_2	3	6	8
t-PO_4=	15	29	39
O-PO_4=	23	47	62
Eh	5	9	12
NO_3NO_2-N	3	6	7
TOC	5	9	12
SO_4=	4	7	9
Fe_T	6	11	15
K	7	13	18
Ca	6	11	15
Mg	5	11	14
Cl^-	8	16	21
Na	5	11	14
Alk	8	16	22
Ion Balance	8	16	22
Temp Cell	10	19	25
VOC	10	19	25
Cond	8	16	21
TOX	8	16	21
Temp Well	9	18	24
NVOC	9	118	24

Table 3. Estimated Ranges of Sampling Frequency (in Months) to Maintain Information Loss at < 10% for Selected types ofChemical Parameters

Type of Parameter	Pristine Background Conditions	Contaminated	
		Upgradiant	Downgradient
Water Qulaity			
Trace constituents (< 1.0 mg·L-1)	2 to 7	1 to 2	2 to 10
Major constituents	2 to 7	2 to 38	2 to 10
Geochemical			
Trace constituents (< 1.0 mg·L-1)	1 to 2	2	1 to 5
Major constituents	1 to 2	7 to 14	1 to 5
Contaminant Indicator			
TOC	2	3	3
TOX	6 to 7	24	7
Conductivity	6 to 7	24	7
pH	2	2	1

Conclusions

Sampling and analytical errors can b controlled to within about ±20% of t annual mean inorganic chemical constituent concentration in ground water if the protocols are properly designed and executed. The use of previously published guides for ground-water monitoring can provide reproducible, accurate results for such studies.

The results of the study concentrate mainly on inorganic chemical constituents in ground water. The statistical characteristics of the time-series data for reactive chemical constituents (e.g., Fe(II), sulfide, H_2O_2, O_2 and NO_2^-) disclose that temporal variability is often lower than the magnitude of concentration changes observed during purging of stagnant water prior to sampling. This means that improper well purging can result in gross errors and the introduction of artifacts into ground-water quality datasets.

June 1991

ENVIRONMENTAL SOFTWARE FROM EMSL-LV

Prepared by

Lockheed Engineering & Sciences Company
Environmental Programs Office
1050 E. Flamingo Rd.
Las Vegas, Nevada 89119

Contract Number 68-C0-0049

Work Assignment Manager
J. Jeffrey van Ee
Exposure Assessment Research Division
Environmental Monitoring Systems Laboratory - Las Vegas
P.O. Box 93478
Las Vegas, Nevada 89193-3478

ENVIRONMENTAL MONITORING SYSTEMS LABORATORY - LAS VEGAS
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
Las Vegas, Nevada 89193-3478

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INTRODUCTION

The Environmental Monitoring Systems Laboratory (EMSL-LV) is committed to the development of quality software that is critical to the monitoring and remediation efforts of the U.S. EPA Regions. EMSL-LV has undertaken the development of expert systems, computerized information systems, decision support systems, and "smart" advisors to provide easy access to the specialized knowledge necessary to meet the decision-making responsibilities in the monitoring and remediation of hazardous waste sites.

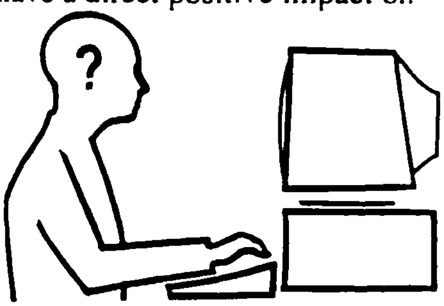
Our early work focused on the computerization of tasks that were previously manually performed and labor intensive. These software packages, such as the widely used Computer-Aided Data Review and Evaluation (CADRE) program, met with great success at many levels and paved the way for further environmental software development.

The next generation of computerization included software capable of addressing specialized skills such as geophysics, geostatistics, and sampling protocols. Our computer programmers work along with the scientists in these areas to ensure technical accuracy as well as ease of use.

Now we are looking at the exciting applications that will be possible with emerging CD-ROM, Hypertext, and Multimedia technology. As always, **your needs guide our research.** Following the series of fact sheets and informational material in this catalog, you will find a brief survey form. Please take a few minutes to complete it and return it to the EMSL-LV. We would like to learn of your interests.

Expert System and Environmental Software Development

EMSL-LV supports EPA decision-making and environmental data processing through the development of expert system and conventional software with environmental application. Several systems are already in use and others are under development. The applications targeted by EMSL-LV have a direct positive impact on the quality of the environmental data obtained by the Agency and the appropriateness of the data analysis and interpretation. This environmental software is customized to the needs of the regional user. EMSL-LV provides follow-up support to all users.



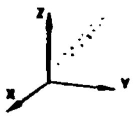
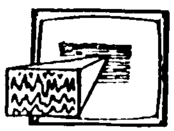
OVERVIEW OF SOFTWARE PACKAGES

EMSL-LV software development efforts center on computerization of waste site characterization. Software packages can be used for the various phases of waste site evaluation. Some programs assist in the project planning while others are used for the analysis of collected data. All of the packages contribute to the improvement of data quality. This section presents an overview of our software applications to different stages of environmental data collection projects.

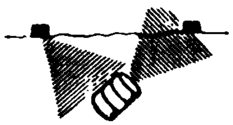
Preliminary Evaluation:	The Geophysics Advisor Expert System assists in the selection of geophysical monitoring methods
Field Sampling:	ASSESS assists in the planning of soil sampling events with appropriate quality control samples to determine sampling errors and their sources. A computerized Hypertext version of the document, detailing the ASSESS approach, "A Rationale for the Assessment of Errors in the Sampling of Soils," is available also. The Soil Sampling Expert System (ESES) is under development to assist in the planning of soil sampling for metal contaminants.
Sample Analysis:	The Smart Method Index (SMI) aids in the selection of analytical methods. SMI provides access to data bases of chemical, physical, and radiological methods, as well as state action limits for drinking water quality parameters.
Data Validation:	The Computer-Aided Data Review and Evaluation System (CADRE) performs data validation of Contract Laboratory Program organic analysis results. A CLP inorganic version is under development.
Data Analysis and Interpretation:	Geo-EAS provides full geostatistical analysis capabilities for spatially-related data. The Scout software helps determine anomalous data points in multivariate data (outliers). These packages work together and provide advanced graphic capabilities.

ASSESS, CADRE, Geo-EAS, Geophysics Advisor, the Hypertext Rationale, Scout, and SMI are currently available directly from EMSL-LV or through the Center for Environmental Research Information (CERI). To request a software package of interest please fill out the enclosed survey sheet.

Expert Systems and Environmental Software Developed by EMSL-LV

	SYSTEM	FUNCTION AND FEATURES
	GeoEas	Performs geostatistical analysis on spatially-distributed environmental data. Includes kriging, graphics, and plotting capabilities.
	SCOUT	Assists in exploratory data analysis. Identifies multivariate outliers, determines the variable(s) in which the anomaly occurred, and displays the data set through interactive three-dimensional graphics.
$\sigma_T^2 = \sigma_S^2 + \sigma_A^2$	ASSESS	Calculates measurement errors for soil sampling based on results from appropriate quality assurance samples.
	Rationale for Assessing Errors In the Sampling of Soils	Explains a soil sampling quality assurance approach in a computerized document through the use of hypertext and provides access to the ASSESS software.

Expert Systems and Environmental Software Developed by EMSL-LV

	SYSTEM	FUNCTION AND FEATURES
	**Geophysics Expert Advisor**	Provides assistance on the use of geophysical monitoring methodology for hazardous waste site assessments. Uses expert system techniques for method selection.
	**Environmental Sampling Expert System (ESES)**	Assists in preparation of field sampling plans to measure groundwater contamination and metal pollution in soil. Combines expert system and hypertext techniques for decision support and help.
	**Computer-Aided Data Review and Evaluation (CADRE)**	Performs semi-automated data validation for the Superfund Contract Laboratory Program multi-method analytical results.
	**Smart Method Index (SMI)**	Provides natural language access to various EPA analytical method and standard data bases.

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Systems Laboratory
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Las Vegas NV 89193-3478

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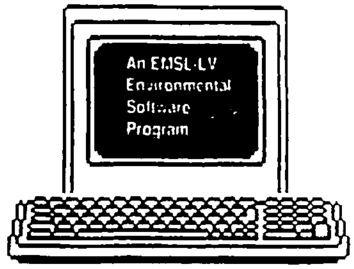
TECHNOLOGY SUPPORT PROJECT

ASSESS: A Quality Assessment Program



INTRODUCTION

ASSESS is an interactive program designed to assist the user in statistically determining the quality of data from soil samples taken at a hazardous waste site. EMSL-LV scientists have developed this public-domain, user-friendly Fortran program to assess precision and bias in the sampling of soils. The total error in a sampling regimen is the sum of measurement variability and natural variability of the contamination. It is the field scientist's challenge to mitigate the measurement variability by careful sample-taking, thoughtful sampling design, and the use of recommended quality assessment samples. The greatest potential for error, both random and bias, is in the sampling step. Field conditions, tool contamination, operator differences, all can affect variability and bias in a sample before it gets to the analytical step.

The value of ASSESS is its ability to detect and isolate error at critical steps in the sampling and measurement function. Installation is simple and is described in the User's Guide referenced at the end of this text.

FEATURES

ASSESS plots graphics directly on the screen to give the user a quick look at data or results. All graphics can be formatted to give hard copy via pen plotters or other graphics printers.

ASSESS checks for missing data and for data input errors of sufficient magnitude to fall outside numeric parameters that have been previously set.

Reports and plots can be incorporated into WordPerfect.

SCREENS AND MENUS

After an introduction screen, ASSESS presents screens and menus beginning with the Data Quality Objectives (DQO) Screen. The user inputs known information about the site and sampling method and desired confidence ranges.

Next, the user may choose the Sampling Considerations Screen. This screen allows entry of further specifics about the field sampling, such as, number of samples taken, number of batches analyzed, cost, and batch data.

The next screen is the Historical Assessment Screen that provides options for entry of historical data that may be critical to the interpretation of this sampling.

A Quality Assessment Data Screen follows that allows the user to view and edit the quality assessment data that are called for in the parent document, *A Rationale for the Assessment of Errors in the Sampling of Soils*, referenced at the end of this fact sheet. These quality assessment samples are fundamental to the successful use of ASSESS. They include samples that will check for and evaluate error in every sampling step. At this point, it is possible to produce scatter plots to visually inspect the contribution to the total error that is made by any particular quality assessment sample with the confidence in the error estimates being a function of the number of data.

The Transforms Screen follows and it gives the user a method for applying unary or binary operations to the entire data set. For example, the field scientist or data interpreter may wish to truncate the data, view the plot as a log or ln function, or perform a basic mathematical operation on all data.

The Results Screen displays variances for sample collection, batch dissimilarity, subsampling error, and handling differences. This screen also shows the total measurement error. A report of the results and a list of historical information and the quality assessment data may be saved to a file or printed.

ASSESS is based on the use of field duplicates, splits, and performance evaluation samples that isolate and assess variability throughout the measurement process. An option is provided for the use of duplicates and splits in the calculation of variability when inadequate types and numbers of performance evaluation samples exist.

DATA FILES

ASSESS incorporates simple ASCII text files that can be created with any text editor. Two output files can be produced by ASSESS, one of which can be read as a data file by ASSESS and the other, which is not ASSESS readable, gives a report-like document. A third type is provided so that the user may edit an input file without entering all the data through ASSESS.

STATUS

ASSESS is currently available in Version 1.0. This is a prototype environmental software package. Further development is planned and input from field scientists and EPA Regional personnel is solicited so that the next version may be more tailored to user needs.

ASSESS is based on the EPA publication, *A Rationale for the Assessment of Errors in the Sampling of Soils*, and it is strongly recommended that users familiarize themselves with the concepts in that document before trying to apply ASSESS.

HARDWARE REQUIREMENTS

Hardware requirements for using ASSESS are:

- IBM PC (or compatible)
- 1.2 MB floppy disk drive 5 1/4" (or 3 1/2" DD or HD)
- Minimum graphics hardware is Hercules graphics card, monochrome display with graphics capabilities, CGA and EGA
- Minimum 512 K RAM
- Math coprocessor chip is recommended but not required

REFERENCES

ASSESS User's Guide, U.S. EPA Report, EMSL-LV, in press.

van Ee, J. J., L. J. Blume, and T. H. Starks, *A Rationale for the Assessment of Errors in the Sampling of Soils*, EPA Report, EPA/600/4-90/013, May 1990.

FOR FURTHER INFORMATION

For copies of the ASSESS program, send preformatted floppy disks with capacity of:

2 3 1/2" DD,
1 3 1/2" HD, or
1 5 1/4" HD

to:

Mr. J. Jeffrey van Ee
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

For general questions regarding the use of ASSESS at a site, contact:

Technology Support Center
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2270/734-3207
FTS 545-2270
FAX/FTS 545-2637

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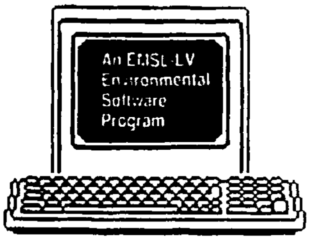
CADRE: A Data Validation Program



INTRODUCTION

The Environmental Monitoring Systems Laboratory - Las Vegas (EMSL-LV) has developed a computer software system to aid environmental scientists and data analysts in the evaluation of data generated by the Contract Laboratory Program (CLP). This system, CADRE (Computer-Aided Data Review and Evaluation) assists in the validation of results from various CLP methods.

CADRE provides data analysts with a quick and reliable method for examining data that will be used for decision making at hazardous waste sites. The program automates the phases of data validation that involve electronic-format data. The data validation process involves comparison of quality control (QC) indicators used in the analysis with pre-established data quality criteria. Non-compliant data are qualified with appropriate codes to indicate the severity of the defect. The final assessment of the data is made by the data reviewer, using the information provided by CADRE.

Examples of QC parameters that are checked by CADRE are: holding time, blanks, calibration, and precision.

FEATURES

CADRE can read data in several CLP electronic formats. It checks for data completeness, and allow the user to edit data. After the validation is complete, CADRE reports the results.

CADRE can be customized by the user to validate data collected using several methods in the CLP. Users can configure CADRE to examine different compounds, alternate quantitation limits, or varying QC parameters.

Another customization of CADRE involves changing data validation criteria to meet the needs of a modified method. The user can choose, for example, to allow a longer holding time if the compound of interest is unlikely to volatilize or degrade. The ability to modify CADRE's specific data quality codes provides the user with greater flexibility and responsibility.

To protect the data from tampering and from human error, a layered security system allows each user access to the program features he or she needs.

The program blends ease of use with a sophisticated screen system. Knowledge of data validation rationale and microcomputer operation are recommended for the effective use of CADRE. A user's guide, training courses, and technical user support are available from the EMSL-LV.

CLP ORGANIC VERSION

The CLP ORGANIC version of CADRE evaluates data from CLP analysis of volatile, semivolatile, and pesticide compounds. Volatile and semivolatile organic compounds are analyzed by gas chromatography/ mass spectrometry (GC/MS). Pesticide analysis is a GC method.

CLP ORGANIC CADRE can be customized to evaluate modified versions of these routine analyses. It can use alternate data validation criteria selected by the user.

Data can be read by CLP ORGANIC CADRE from the CLP Analytical Results Database (CARD) or from Agency standard format files.

Checks performed by CADRE include:

- quantitation limits
- holding time
- GC/MS tuning
- calibration
- internal standards
- system performance
- surrogate recovery
- matrix spike recovery
- precision of duplicates
- contamination of blanks

QUICK TURNAROUND METHOD VERSION

The Quick Turnaround Method (QTM) version of CADRE reviews data obtained by the QTM methods. There are QTM methods available for VOC, PAH, phenols, pesticides, and PCB. These methods are based on the need for fast extraction and chromatographic analysis within 2 days. For speed and simplicity, QTM CADRE works in conjunction with other software for electronic data transmission from the laboratory to the user through the Agency communications network.

QTM CADRE is completely automated. The data reviewer needs only to set up the system and interpret the reports.

ADVANTAGES AND LIMITATIONS

The use of computerized data evaluation is changing the workplace for many data reviewers. The automation of routine checks will give the individual more time to thoughtfully interpret the results.

It is anticipated that increased accessibility of computer hardware to personnel will lead to greater demand for programs like CADRE that will streamline routine work. Currently, CADRE is being developed for inorganic methods.

Advantages	Limitations
• Fast, complete, and consistent data validation • Easy customization for modified methods • Reduction of human error • Automated report generation	• Requires availability of powerful computer for efficient use • Reviewer judgement needed for some decisions • Available for CLP organic and QTM methods only • Needs complete data set in electronic format

HARDWARE REQUIREMENTS

Hardware requirements for using CADRE are:

- IBM PC (or compatible)
- MS-DOS (or equivalent)
- Hard disk drive
- 640 K RAM

A math coprocessor chip is recommended but not required. For easy use, a mouse pointer is recommended.

REFERENCE

Simon, A. W., J. A. Borsack, S. A. Paulson, B. A. Deason, and R. A. Olivero. Computer-Aided Data Review and Evaluation: CADRE CLP Organic User's Guide, U.S. EPA, June 1991.

FOR FURTHER INFORMATION

For further information on CADRE, contact:

Mr. Gary Robertson
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2215
FTS 545-2215

For information about the Technology Support Center at EMSL-LV, contact:

Mr. Ken Brown, Manager
Technology Support Center
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2270
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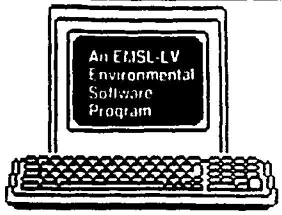
Geo-EAS: Software for Geostatistics



INTRODUCTION

The Environmental Monitoring Systems Laboratory-Las Vegas (EMSL-LV) can meet the needs of scientists who work with spatially distributed data. The complexity of contaminant distribution and migration at hazardous waste sites requires a mathematical method that is capable of interpreting raw data and converting them to useful information. Geostatistics began in the mining industry and has grown to include applications ranging from microbiology to air monitoring.

Though the application of geostatistics is crucial to the delineation of buried contaminants, not every field scientist can be expected to develop customized geostatistical algorithms for individual sites. Geostaticians at the EMSL-LV developed a software package, Geo-EAS in 1988. The current version, Geo-EAS 1.2.1, was released in 1990. This program offers the environmental scientist an interactive tool for performing two-dimensional geostatistical analyses of spatially distributed data.

THE METHODOLOGY

Geostatistical methods are useful for site assessment and monitoring where data are collected on a spatial network of sampling locations. Examples of environmental applications include lead and cadmium concentrations in soils surrounding smelters, and sulfate deposition in rainfall. Kriging is a weighted moving average method used to interpolate values from a data set onto a contouring grid. The kriging weights are computed from a variogram, which measures the correlation among sample values as a function of the distance and direction between samples.

Kriging has a number of advantages over other interpolation methods:

Smoothing
Kriging regresses estimates based on the proportion of total sample variance accounted for by random noise. The noisier the data set, the less representative the sample and the more they are smoothed.

Declustering
The kriging weight assigned to a sample is lowered to the degree that its information is duplicated by highly correlated samples. This helps mitigate the impact of oversampling hot spots.

Anisotropy
When samples are highly correlated in one direction, kriging weights will be greater for samples in that direction.

Precision
Given a variogram representative of the area to be estimated, kriging will compute the most precise estimates from the data.

Estimation of the variogram from sample data is a critical part of a geostatistical study. Geo-EAS is designed to make it easy for the novice to use geostatistical methods and to learn by doing. It also provides sufficient power and flexibility for the experienced user to solve practical problems.

EQUIPMENT REQUIREMENTS

Geo-EAS was designed to run under DOS on an IBM, PC, XT, AT, PS2, or compatible computer. Graphics support is provided for Hercules, CGA, and EGA. At least 512 Kb of RAM is required, but 640 Kb is recommended. An arithmetic co-processor chip is strongly recommended due to the computationally intensive nature of the programs, but is not required. Programs may be run from floppy disk but a fixed disk is required to use the programs from the system menu. The system storage requirement is approximately three megabytes. For hardcopy, a graphic printer is required. Support is provided for most plotters. Design features such as simple ASCII file formats and standardized menu screens, give Geo-EAS flexibility for future expansion. It is anticipated that Geo-EAS will become a significant technology transfer mechanism for more advanced methods resulting from the EMSL-LV research and development programs.

Geo-EAS software and documentation are public domain, and may be copied and distributed freely.

MAPS AND MENUS

The Geo-EAS programs use an ASCII file structure for input. The files contain a header record, the number of variables, a list of variable names and units, and a numeric data table.

All Geo-EAS programs are controlled interactively through menu screens which permit the user to select options and enter control parameters. The programs are structured to avoid a "black box" approach to data analysis. Several of the more complex programs permit the user to save and read parameter files, making it easy to rerun a program.

The programs DATAPREP and TRANS provide capability for manipulating Geo-EAS files. Files can be appended or merged, and variables can be created, transformed, or deleted. Transformation operations include natural log, square root, rank order, indicator, and arithmetic operations.

POSTPLOT creates a map of a data variable in a Geo-EAS data file. Symbols representing the quartiles of the data values or the values themselves are plotted at the sample locations.

STAT1 computes univariate statistics, such as mean and standard deviation, for variables in a Geo-EAS data file, and plots histograms and probability.

SCATTER and XYGRAPH both create x-y plots with optional linear regression for any two variables in a Geo-EAS file. SCATTER is useful for quick exploratory data analysis, while XYGRAPH provides additional capabilities such as multiple "y" variables, and scaling options.

PREVAR creates an intermediate binary file of data pairs for use in VARIO, which computes and displays plots of variograms for specified distance and directional limits.

Variogram models can be interactively fitted to the experimental points. The fitted model may be the sum of up to five independent components, which can be any combination of nugget, linear, spherical, exponential, or Gaussian models. XVALID is a cross-validation program which can test a variogram model by estimating values at sampled locations from surrounding data and comparing the estimates with known values.

KRIGE provides kriged estimates for a two-dimensional grid of points. A shaded map of estimated values is displayed on a Geo-EAS file of kriged grid results.

CONREC generates contour maps from a gridded Geo-EAS data file, usually the output from KRIGE. Options are provided for contour intervals and labels and degree of contour line smoothing.

REFERENCE:

Isaaks, E. H. and R. M. Srivastava, *An Introduction to Applied Geostatistics*, Oxford University Press, New York, 1989.

AVAILABILITY:

For further information about Geo-EAS, contact Dr. Evan Englund. Government agencies and academic or research institutions can obtain a copy of Geo-EAS with User's Guide at no charge by sending three pre-formatted high-density diskettes (5-1/4" or 3-1/2") to:

Dr. Evan J. Englund
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory-Las Vegas
P.O. Box 93478
Las Vegas, NV 89193-3478
FAX: (702) 798-2248
FTS: 545-2248

Others can obtain a copy for a distribution charge of approximately $45 (includes diskettes, User's Guide, and USA shipping) from either:

ACOGS	*or* COGS
P.O. Box 44247	P.O. Box 1317
Tucson, AZ 85733-4247	Denver, CO 80201-1317
FAX: (602) 327-7752	Phone: (303) 751-8553

FOR FURTHER INFORMATION:

For information about the Technology Support Center at EMSL-LV, contact:

Mr. Ken Brown, Manager
Technology Support Center
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory-Las Vegas
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2270

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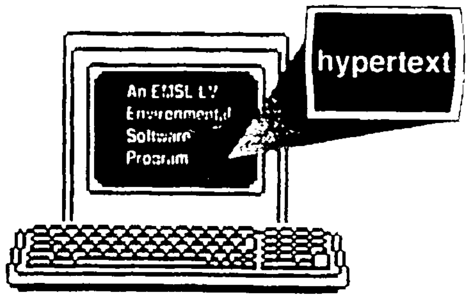
TECHNOLOGY SUPPORT PROJECT

Hypertext: A Showcase for Environmental Documents



INTRODUCTION

The amount of "required reading" for those engaged in hazardous waste site remediation is overwhelming. Documents pile up - often leaving the scientist no option but to briefly review the abstract or the executive summary. Fortunately, there exists a computer software tool, hypertext, that allows for documentation on disk that can provide all readers/users with various layers of information. The tiered knowledge in hypertext makes it ideal for experts in the field of the publication who can scan through the general information and concentrate on a particular section. It is also suited to the novice in the document's area who can access highlighted areas for in-depth definitions of unfamiliar terms, full-screen presentations of tables and figures, and references to ancillary works.

Hypertext is an easy-to-use, timesaving reading tool for the overburdened scientist. The ability to read an electronic book helps each reader optimize the information-time ratio.

Scientists at the EMSL-LV have used hypertext on a frequently used document, "A Rationale for the Assessment of Errors in the Sampling of Soils" by J. Jeffrey van Ee, Louis J. Blume, and Thomas H. Starks. The original hardcopy document is about 60 pages long, and contains 4 figures and 8 tables. The document also contains several formulas that may be unfamiliar to many users. The hypertext version fits on a floppy disk, keeps general information "hidden" unless it's requested by a novice user, and highlights frequently used tables for easy access.

Hypertext can be applied to any document that exists in digital form. The level of hypertext a document needs depends on the complexity and length of the original document and the anticipated expertise of the reading audience.

THE RATIONALE DOCUMENT

The Rationale mentioned above addresses the complexity of the sampling and analysis of soils for inorganic contaminants from experimental design to the final evaluation of all generated data. Sources of error abound but they can be successfully mitigated by careful planning or isolated by intelligent error assessment. Error can be either biased or random. Biased error is indicative of a systematic problem that can exist in any sector of soils analysis, from sampling to data analysis. The first step in analysis of variability is to establish a plan that will identify errors, trace them to the step in which they occurred, and account for variabilities to allow direct corrective action to eliminate them.

Error assessment should be understood by the field scientist and the analyst. To implement the ideas in the Rationale document and aid scientists in the estimation and evaluation of variability, the EMSL-LV has developed a computer program called ASSESS. By applying statistical formulas to quality assurance data entered, ASSESS can trace errors to their sources and help scientists plan future studies that avoid the pitfalls of the past.

HOW HYPERTEXT WORKS

Scientists at the EMSL-LV took the disk containing the Rationale document and extracted sections such as the Table of Contents, tables, figures, and certain equations and formulas. These sections appear separately when selected in the new hypertext version. Then, throughout the document, certain words and phrases were highlighted so definitions can be accessed by a keystroke.

When a reader receives a hypertext document on disk, he or she can look at the Table of Contents and decide which sections to read. By selecting, for example, the section entitled "background",

HOW HYPERTEXT WORKS (Continued)

the reader can be briefed on the scope of the document. A term within the Background section, e.g., "representative" may be highlighted. Readers wishing the definition of "representative" as used in this document may get an immediate clarification. In traditional (linear) hardcopy documents, a reader must either wait for the definition to be clarified in text or seek an external definition through outside reference materials.

BRIDGE TO ASSESS

The Rationale document is the basis for an EMSL-LV environmental software program called ASSESS. The philosophy and statistical background in the document is exercised practically with ASSESS, which is also available on disk. The hypertext version of the Rationale document prepares the reader to use ASSESS and also serves as a physical link to the program. The last item on the Rationale document hypertext menu is "ASSESS". After becoming familiar with the concepts in the document, the user may select "ASSESS" to begin to use the software.

This hypertext linkage of two or more documents or programs can simplify and clarify many software applications for novice users. By providing ASSESS users with the technical background in its development and Rationale document readers with a viable program, hypertext serves all levels of users in error-tracing in the complex application of soil sampling.

ADVANTAGES AND LIMITATIONS

Increased availability of computer workstations and the development of user-friendly programs have made hypertext an almost unqualified bonus to busy readers/users. Hypertext is easily and effectively used for: acronyms and abbreviations, terms and phrases, tables and figures, graphics, formulas and references.

Advantages	Limitations
• Streamlined and non-interruptive	• Availability of computer with appropriate hardware
• Linkage to other hypertext documents	• Some computer literacy required
• Time-saving for expert; instructional for novice	

HARDWARE REQUIREMENTS

Hardware requirements for using this hypertext package are:

- IBM PC (or compatible)
- 1.2 MB floppy disk drive, 5 1/4" (or 3 1/2" DD or HD)
- Minimum graphics hardware card, monochrome display with graphics capabilities, VGA and EGA
- Minimum 640 K RAM
- Math coprocessor chip is recommended but not required

REFERENCES

Text, ConText, and HyperText: Writing with and for the Computer, E. Barrett, ed., The MIT Press, 1988.

van Ee, J. J., L. J. Blume, and T. H. Starks, A Rationale for the Assessment of Errors in the Sampling of Soils, EPA Report, EPA/600/4-90/013, May 1990.

FOR FURTHER INFORMATION

For more details on Hypertext and the Rationale document, contact:

Mr. J. Jeffrey van Ee
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2367

For information about the Technology Support Center at EMSL-LV, contact:

Mr. Ken Brown, Manager
Technology Support Center
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2270

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Las Vegas NV 89193-3478

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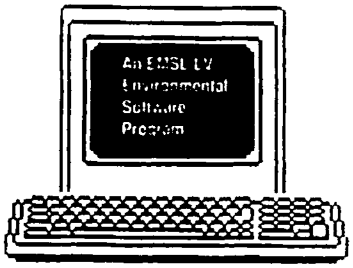
Scout: A Data Analysis Program



INTRODUCTION

The complexities of correct data interpretation challenge environmental scientists everywhere. Environmental software packages have been developed to address the various needs of data analysts and decision makers. One frequent need is for the reliable determination of outliers in a data set. Scout is a program developed to identify multivariate or univariate outliers, to test variables for lack of normality, to graph raw data and principal component scores, and to provide output of the results of principal component analysis. Scout provides interactive graphics in two and three dimensions. There are many advantages of a graphical display of data in a multidimensional format: it allows a quick visual inspection of data, it accentuates obvious outliers, and it provides an easy means of comparing one data set with another. Scout has the flexibility to allow viewing and limited editing of a data set. Scout features on-line help, with a "built-in" users guide. Scout is a valuable addition to the library of environmental software packages available from the EMSL-LV.

FEATURES/ SPECIFICATIONS

Scout is a public domain, Turbo Pascal program that is user friendly and menu driven. Scout reads ASCII data files that are in Geo-EAS format. The first line of a Geo-EAS data file is a comment line, generally used to describe the origin of the data. The second line of the file must contain the number of variables - always a number greater than or equal to 1 and less than or equal to 48. The next lines contain variable names in the first 10 columns and the associated values in the next 10 columns. Scout is compatible with most IBM personal computers that have an EGA, VGA, or Hercules graphics system. Scout will run with or without a math co-processor, but this feature is preferred for handling floating point calculations. A fixed disc drive is strongly recommended because Scout performs many transfers between memory and disc during execution. On-line help is available throughout Scout and the user can access it by selecting the "System" option in the main menu and then selecting "Information".

MENUS

There are five menus in Scout: file management, data management, outliers, principal components analysis, and graphics.

After the introduction screen, the user should choose the "File Management" option on the main menu. This option allows the user to load the Scout data file or read an ASCII data file and to access various subdirectories of data. Scout saves data files in two formats: binary and the Geo-EAS ASCII format. Scout has the ability to search for file names, including wild cards. The current search string is printed at the top of the window. Other options in this area include "Write ASCII Data File" for saving the Scout file and "Merge Two Data Files" for combining two files into one.

The second menu is "Data Management" which includes options for editing data, variables, and observations. This menu also displays summary statistics, such as mean, standard deviation, and variance. Additionally, there is a "Transform" option which allows the user to test each variable for lack of normality, based on the Kolmogorov-Smirnov test at the five percent significance level. The critical value, test statistic, and apparent conclusion are displayed. The Anderson-Darling test is also performed and a horizontal histogram is displayed at the bottom of the screen.

Menu three is "Outliers", which applies two powerful tests for discordancy to the data: the (Mahalanobis') generalized distance, and the

(Continued)

MENUS (Cont.)

Mardia's multivariate kurtosis test. After selecting "Outliers", the user can tell Scout which variables to test, or use the default wherein Scout tests all variables. The user must then decide to use the generalized distance test or Mardia's kurtosis. If a large proportion of the data is identified as discordant, the user should be cautious that the problem may be due to lack of multinormality. The outlier report may be displayed, sent to a file, or printed. By selecting "Causal Variables" the user can test each variable for its contribution to the discordant nature of the outlier. This option can trace some independent errors, such as typographical or transcription errors.

The fourth menu is "Principal Component Analysis" which allows the user to select the variables to be used and to display covariance or correlation. By choosing the "View Components" option, the user can view the eigenvectors and eigenvalues of the PCA. Scout will prompt the user to specify whether or not to include previously determined outliers. The user can graph the component scores, which are products of the eigenvectors and the standardized observation vectors. A "Transform Data" option is available to change the data in memory from observations to component scores.

The fifth, and final, menu is "Graphics" which features two graphics systems: two-dimensional and three-dimensional. The two-dimensional system is used to display scatter plots and x-y plots. The three-dimensional system is used to display three variable plots, which can be rotated to illustrate the added dimension. The user can modify graph colors and shapes. Graphics screens may be saved by writing to a file on disk. The user can change the size of the graph by zooming in or out using the "+" or "-" keys. The four arrow keys are used to rotate the graph. The left and right arrows rotate the graph around the Z axis. The up and down arrows rotate the graph around an imaginary horizontal axis that passes through the origin. Another feature, "Search Observation Mode", is available and allows users to identify the individual observations shown on the graph.

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Garner, F. C., M. A. Stapanian, and K. E. Fitzgerald, Finding Causes of Outliers in Multivariate Data, J. Chemometrics, in press.

FOR FURTHER INFORMATION

For copies of the Scout program, contact:

Mr. Jack Teuschler
U.S. Environmental Protection Agency-CERI
26 King Drive
Cincinnati, OH 45268

(513) 569-7314
FTS 684-7314

For additional technical information about Scout, contact:

Dr. George Flatman
U.S. Environmental Protection Agency
Environmental Monitoring
Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2628
FTS 545-2628

For information about the EMSL-LV Technology Support Center, contact:

Mr. Ken Brown, Manager
Technology Support Center
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89193-3478

(702) 798-2270
FTS 545-2270

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Environmental Protection
Agency

Environmental Monitoring
Systems Laboratory
P.O. Box 93478
Las Vegas NV 89193-3478

January 1991

Research and Development

EPA

ASSESS

User's Guide

assess

NOTICE

Version 1.0 of this software is a prototype. Additional modifications are planned for the future. The information in this document does not represent the views or policy of the Environmental Protection Agency.

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Section 1

Introduction

1.1 OVERVIEW

ASSESS is an interactive program designed to assist the user in statistically determining the quality of data from field samples. The program permits quality assessment data and historical information (historical information is for notational purposes only) such as data quality objectives, sampling considerations, and historical assessments to be saved. Measurement-error variances are computed. Scatter plots of the variance (represented as $\sqrt{2}$ times the standard deviation) versus the average concentration may be produced for Routine Samples (RS) with either Field Duplicates (FD) or Preparation Splits (PS). Transforms may be applied to the entire data set. Error bar graphs of variance estimates from quality assessment (QA) samples may be produced. Hardcopies of all plots may be obtained by depressing the <P> key. The plots may also be stored in a file of device independent plotting commands (metacode). An HPGL plotter instruction file may be produced using the program HPPLOT with the metacode file as input. The historical information, measurement-error variances, and data set may be written in a report format to either an output file or sent to a printer. The printer must be either an Epson- or IBM-compatible dot matrix printer, HP Laserjet, or HP Deskjet.

ASSESS may be used to provide a foundation for answering two basic questions:

How many, and what type, of samples are required to assess the quality of data in a field sampling effort? How can the information from the QA samples be used to identify and control sources of error and uncertainties in the measurement process?

Once the analytical results are received, bias and precision values will be computed. Note that ASSESS will only compute the precision.

An alternative QA design that does not employ field evaluation samples (FES) and external laboratory evaluation samples (ELES) is also discussed and error variances are computed.

ASSESS uses two temporary files called scratch files to store and process data read from an ASSESS data file. These scratch files are assigned the names XXXXXXXX.XXX and ZZZZZZZZ.ZZZ.

The concentrations (units) of the samples may be specified for notational purposes, but unit conversions cannot be made by ASSESS.

It is recommended that the EPA publication "A Rationale for the Assessment of Errors in the Sampling of Soils"(1), from which the program ASSESS has been derived, be used in conjunction with this user manual.

Please forward any questions, comments, or bug reports to the following address:

Jeff van Ee (Assess)
USEPA EMSL-LV, EAD
P.O. Box 93478
Las Vegas, NV 89193-3478

1.2 EQUIPMENT REQUIREMENTS

ASSESS was designed to run under DOS (Disk Operating System) on an IBM PC, XT, AT, PS2, or compatible. Graphics capability is not required, but is highly recommended as graphics output is produced. Graphics support is provided for the Hercules graphics card, laptops with monochrome displays having graphic capabilities, the Color Graphics Adapter (CGA), and the Enhanced Graphics Adapter (EGA). Support for Video Graphics Array (VGA) is not available, however, VGA does emulate EGA and therefore graphics support is provided for VGA indirectly. At least 512 kilobytes (Kb) of random access memory (RAM) is required, but 640 Kb is recommended. An arithmetic co-processor chip is recommended due to the computational intensive nature of the program, but is not required for use. ASSESS may be run from floppy diskette or from a fixed disk. The system storage requirement is approximately 420 kilobytes. For a hardcopy of results, a graphics printer (IBM graphics compatible) is required. Support is provided for plotters which accept HPGL plotting commands.

1.3 USER PROFILE

To use ASSESS, one should have some familiarity with personal computers and DOS (Disk Operating System). One should also understand basic DOS commands such as DIR (directory), CD (change directory), and how to insert and use diskettes. For more information on these topics, consult a DOS user's manual. The manual titled "A Rationale for the Assessment of Errors in the Sampling of Soils"(1) must be followed. For a list of references, refer to Appendix B, References.

1.4 INSTALLING THE SYSTEM

1.4.1 *ASSESS Data Files*

ASSESS in its executable form is entirely in the public domain. In the future, it may be downloaded from the U.S. EPA Bulletin Board System.

ASSESS.exe is the only file required to run ASSESS. If a metacode file is to be converted to a file with an HPGL format, then Hpplot.exe and Hershy.bar are required. Hershy.bar is a character font file and is required to execute Hpplot.exe.

The executable file, example data set, and optional files are as follows:

```
ASSESS    .exe    422778 bytes (required)
```

Optional:

```
Standard  .fil      2576 bytes (example data set)
Alt1      .fil      1471 bytes (example data set)
Alt2      .fil      1636 bytes (example data set)
Saved1    .fil      4744 bytes (used for comparison)
Saved2    .fil      3771 bytes (used for comparison)
Barchart  .met      1440 bytes (used for comparison)
Scatter   .met      2880 bytes (used for comparison)
Results   .fil      4744 bytes (used for comparison)
Smdata    .fil      1714 bytes (example data set)
Example   .fil      4744 bytes (example data set)
Hpplot    .exe     98417 bytes (conversion program)
Hershy    .bar    176000 bytes (required with Hpplot.exe)
```

The files denoted as "Used for Comparison" will be created by ASSESS as you run through the program. Therefore, these files may reside somewhere outside the directory where ASSESS resides and thus will not be overwritten.

The source code is written in FORTRAN 77 for the Microsoft (Microsoft Corporation, Redmond, WA) FORTRAN compiler (version 4.01). With the exception of slightly modified proprietary Graflib Version 1.0 (Sutrasoft, Sugarland, TX) subroutines used for generating screen graphics, the source code is also in the public domain.

1.4.2 *Hard Disk Installation*

To install the system on a fixed disk, a subdirectory should first be created (for example, ASSESS). Copy ASSESS.exe and any other optional files into the subdirectory. For more information on creating subdirectories and copying files from a diskette into a subdirectory, refer to your DOS user's manual.

1.4.3 *Using ASSESS on Floppy Diskette*

ASSESS.exe is too large to fit on a 360 kilobyte diskette. This means that if only a 360 kilobyte disk drive (and no fixed disk) is available, then ASSESS cannot be used. Either a 3.5" disk drive or a 1.2 megabyte (or larger) 5.25" disk drive is needed to run both ASSESS and the optional program Hpplot.exe (with Hershy.bar)

1.4.4 *Using ASSESS from DOS*

To run ASSESS or Hpplot from DOS, type ASSESS or Hpplot at the DOS prompt. For example, to start program ASSESS type:

```
ASSESS <enter>
```

ASSESS uses most of the available memory. If an error message occurs after typing ASSESS, try to free other existing memory-resident programs, and type ASSESS to restart the program.

1.5 GRAPHICS

1.5.1 *On-Screen Graphics*

ASSESS plots graphics directly on the screen. This approach is used to provide a quick look at data or program results. Such graphics displays may be printed on a dot-matrix printer. When a graphics screen is displayed, the program will wait for a key to be pressed. Pressing <Q> will cause an interactive screen and menu to be displayed. Pressing <P> will produce a hard copy of the screen on a graphics printer. It is important to make sure that a graphics printer is connected to your computer if you choose this option, or the program will "lock-up". Also make sure that the printer is turned on and "on-line". If the program "locks up", the computer will probably have to be re-started.

1.5.2 *Metacode-Based Graphics*

The graphics displays may also be written to a "metacode" file when the "Save Plot" menu option is selected. A metacode file is a file of device-independent plotting instructions. This file can be converted to a HPGL (Hewlett Packard Graphics Language) formatted file using the program Hpplot (refer to section 1.4.1 *ASSESS Data Files* concerning Hpplot.exe). The advantage of using a metacode file is that higher-quality graphic output can be obtained on a pen plotter or other graphics device. The HPGL format is directly supported by WordPerfect.

Example: To import a metacode file generated by ASSESS into WordPerfect 5.0, perform the following steps*

1.) Generate a metacode file called 'Metacode.met' using ASSESS. Either of the two graphs generated by ASSESS may be saved to a metacode file. Note that the name "Metacode.met" is a generic name and it may be referred to by any other name. The ".met" extension is used as a means of distinguishing these files and the regular ASCII text files.

2.) Run the program HPPLOT. Enter 'Metacode.met' as the input file and 'Metacode.plt' as the output file. HPPLOT will convert 'Metacode.met' to an HPGL formatted filecalled 'Metacode.plt', which is supported by WordPerfect*.

3.) If you have a VGA adapter, the HPGL formatted file may require one more conversion using the WordPerfect conversion program Graphcnv.exe. To convert, call GRAPHCNV, and then enter "Metacode.plt" as the input file and "Metacode.wpg" as the output file. GRAPHCNV will generate "Metacode.wpg" which can be successfully imported into WordPerfect on PC's using a VGA adapter.

1.6 ERROR AND RECOVERY PROCEDURES

Normal Error Processing

ASSESS performs error checking on such items as file existence, file Input/ Output and bounds checking on numeric parameters. When errors of these types are encountered in programs, error messages are displayed on the message line at the bottom of the screen. These messages are displayed in a black-on-white format (reverse video) and are accompanied with a buzz sound. To return to the interactive screen after such a message is displayed, press any key.

Problems

Although ASSESS has been tested and debugged it is still possible that there are situations which will cause ASSESS to "crash" or "fail" (terminate prematurely), or to "lock-up" (pause indefinitely with no response). If ASSESS "locks-up", the computer must be re-started. The problem may be due to a bug, or due to a printer or disk-drive problem (see below).

ASSESS may crash when a binary operation in the Transform menu is chosen which would produce a very large or very small number. An example would be the operation 1.0 / X, or 10 to the power of X, when X is a very small or very large (1.E-1000, 1.E1000). This type of program error cannot be trapped or handled by ASSESS. In such cases the result cannot be produced due to hardware limitations in the precision of the numeric coprocessor (or floating-point emulation software). Since there is no remedy for this situation, the only solution is to avoid such operations.

There are several error conditions which the program was specifically not designed to check for. These involve checking to see if disk or printer peripherals are connected and ready for data transfer. The user should ensure that printers are attached and on-line, or that disk drives have the correct density media and are ready for read/write operations, when Read, Save, or Write options are selected. The following actions are guaranteed to create a "lock-up" situation.

**WordPerfect is a registered trademark of WordPerfect Corporation.*

- Trying to print a text or graphics screen when the printer is not connected or on-line. If a printer is connected, make sure it is turned "on" and is ready to accept output from the computer (on-line). If a printer is not connected to your system, it may be necessary to "re-boot" the computer.
- Accessing a file on a floppy diskette drive when the disk drive door is open, or no diskette is present. In some cases, DOS may respond with a message: Device not ready (Abort, Retry, Ignore). Insert a diskette and press <R> (for Retry). If this does not work, you must re-start the computer.

Section 2

System Operation

2.1 DATA

2.1.1 *ASSESS Data Files*

ASSESS employs a particular format for its data files. An ASSESS data file is an ASCII text file and is different from the Metacode files used by the HPPLOT program. The ASSESS data files may be created with any text editor. For instance, WordPerfect* files may be converted to ASCII text files before being supplied to the program. Make sure your data files are compatible with the input format, or the program will not be able to read them. ASSESS will also operate without an input data file, in which case the screen layout for data input will be self explanatory. Three example data files included with the distribution diskette will be used as examples in this manual. Copy these files into the subdirectory where the Program ASSESS resides. They are called "standard.fil", "alt1.fil", and "smdata.fil". Below is an explanation of the "standard. fil" data file. The format of the other two files is the same and will be discussed later. It is helpful to obtain a print-out of these files using the DOS print command before proceeding to the next section.

Line 1 to 42

These lines of data represent the historical information. The data file includes information about the site, methods, desired accuracy, precision, etc. Note that these input lines are inconsequential to the data processing phase of ASSESS and are merely supplied to keep track of sampling considerations and historical assessments.

Line 43 to End of File - The Data Entries

This is where the data are stored. Each row represents a batch sample consisting of a pair of QA samples. For the regular design, these QA samples are stored under the following columns: Routine Sample (RS), Field Duplicate (FD), Preparation Split (PS), Field Evaluation Sample Pairs (FES1 and FES2), and External Laboratory Evaluation Sample pairs (ELES1 and ELES2).

For the "Alternative QA" design, only FES1 and ELES1 values used for detection of bias are included; and two new columns are provided for Batch Field Duplicates (BFD) and their locations.

**WordPerfect is a registered trademark of WordPerfect Corporation.*

The data may be in "free format" which means that in a given line in the file, values must be separated by at least one space or a single comma. For readability, columns of numbers should line up; although this style is not required. Variable values must be numeric with no embedded blanks. Whenever a value could not be obtained for a variable, a special value of -9999.0 will be assigned to it. This value, referred to as missing, will not be included in the calculations. The file "standard.fil" contains the historical data and 23 batch samples. Examine the contents of this file using the DOS "Type" command or your editor.

Note: Refer to Appendix A for further discussions of the different data file formats.

2.2 INTERACTIVE SCREENS

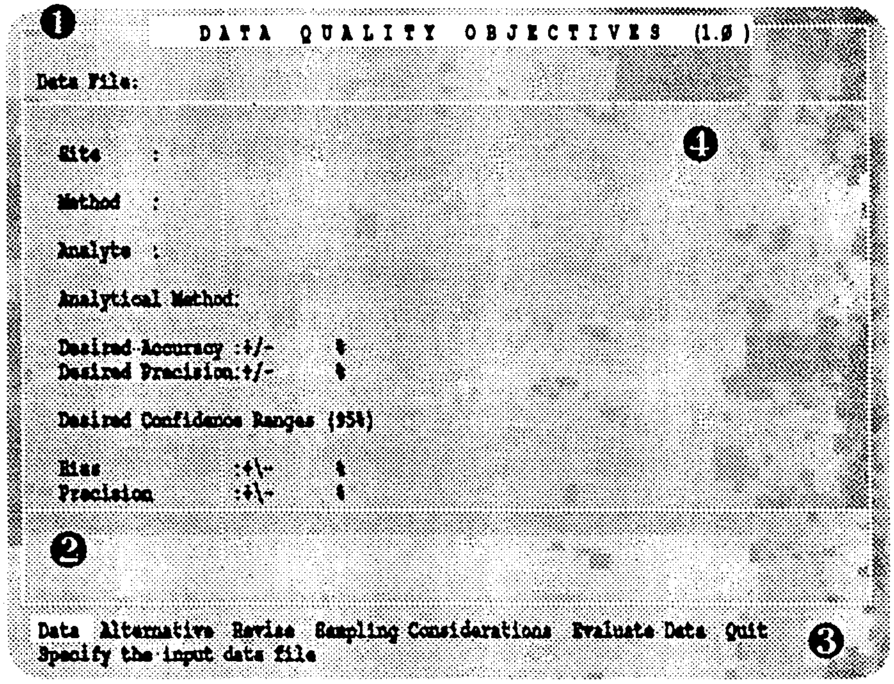
2.2.1 *Screen Format*

This section will show the basic components of screens used in ASSESS. A menu tree of the entire program is presented to observe the flow of the program's interaction.

ASSESS initially displays an introduction screen. Upon pressing any key, the first interactive screen is displayed. ASSESS is composed of several screens for selection of program options and display of results. Figure 2-1 displays the first interactive screen. Below is a description of common components.

Figure 2-1

Example Interactive Screen



❶ The Screen Frame

This is the rectangular box which encloses each screen. Program inputs and results are displayed in this area. Typically, the screen frame is divided into smaller, single-line rectangles. Each of these smaller rectangles contains a functionally related group of one or more input parameters or program results.

❷ The Message Line

This is the rectangle at the bottom of the screen frame. This area is used to display program error messages, yes/no prompts, prompts for additional information, or instructions for using a program option.

❸ The Menu Line

This is the line of text just below the screen frame. It contains a set of menu option names and a highlighted box (cursor bar). The cursor bar can be moved along the menu line by using the <left> and <right> arrow keys. As the cursor bar is moved over a menu option name, a short description of the menu option is displayed on the line just below the menu line. This line is called the menu description line. You may explore the possible choices in a program by moving the cursor bar and reading the descriptive messages which accompany each menu option. To select a menu option, move the cursor bar over the desired menu option name, and press <enter>. An alternative (and faster) way to select a menu option is to press the key which corresponds to the first letter in the menu option name. The result is the same as using the cursor control keys and pressing <enter>. For example, you would choose the "Revise" option by pressing <R> from the main menu.

❹ Parameter Groups

Typically, a functionally related group of program input parameters (fields) are enclosed together on the screen by a single-line rectangle. These groups of parameters are accessed through the menu. When a menu option is selected, a cursor bar appears at the screen field, and a message describing what action to take appears on the message line. When such a group contains several fields, the cursor control keys are used to move to subsequent fields. Exiting from the last field in the group will return the cursor bar to the menu line.

2.2.2. *Types of Screen Input Fields*

Several types of input files are provided to allow flexibility in program parameter specification. Below is a list of these types and an example of each field type in the first screen of ASSESS (Figure 2-1).

Alphanumeric Fields — These fields may contain character strings of alphabetic or numeric characters. Any alphanumeric characters may be entered. The "Data" menu option in the screen of Figure 2-1 requires an alphanumeric value to be entered. To specify a data file name, select the data option on the menu; and type the name of the input data file.

Numeric Fields — Only numeric data may be entered into numeric fields. Some numeric fields will only accept integer (non-decimal) numbers. The program will respond to any erroneous keystrokes (such as alphabetic keys) with a low-pitched error tone. An example of numeric fields in the screen of Figure 2-1 are the desired accuracy and desired precision fields. Only integers may be entered for these two fields.

Toggle Fields — A toggle field is a special type of field which contains a list of 2 or more preset choices. Only one of these choices is displayed in the field. The <space> key is used to change the displayed choice, and the <enter> key is used to make the selection. Two examples of toggle fields in the screen of Figure 2-1 are the "Data" field and the "Alternative" field. Once the data option is selected, the toggle field will contain a "Yes" and "No" in response to the prompt "Do you want to specify a data file <use space bar>:" The toggle field will be highlighted; and each time the <space> key is pressed, "Yes" or "No" will appear. Press the <enter> key to make a selection. If "Yes" is selected, the toggle fields "Input (with labels)" and "Standard (with no labels)" may then be selected. Alternative option allows for two toggle fields, "Yes" and "No", in response to the prompts regarding the sample locations.

Yes/No prompts, prompts for additional information — These prompts are for information which will not be displayed permanently on the screen. They will appear temporarily on the message line. A Yes/No prompt will typically have the form: "Question...<Y/N>?". To respond Yes, press the <Y> key; to respond in the negative, press any other key. A typical Yes/No prompt is the "Do you really want to quit <Y/N>?" prompt which is displayed after the "Quit" (terminate program) option is selected. Another example is when you attempt to write over an existing file.

2.2.3 *The Menu Tree*

ASSESS typically requires input from data files and through interactive screens. These program inputs are arranged in a hierarchy of functionally related groups. Each group or individual program parameter value is accessed through a menu of choices. Some choices will lead to other menus, while some will lead to prompts for groups of one or more inputs. Such an arrangement can be represented in a menu hierarchy as illustrated in Figure 2-2.

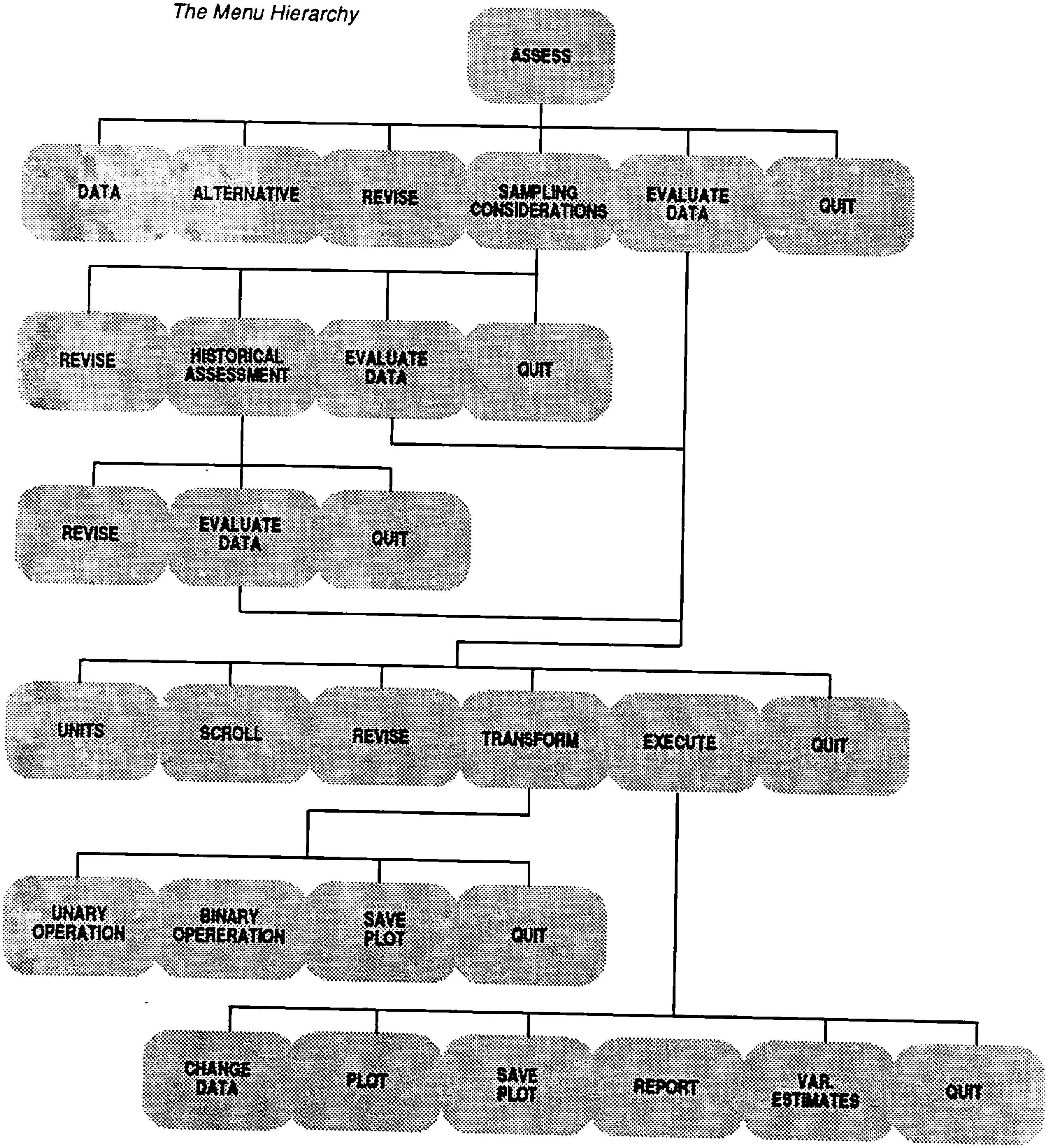
The "menu tree" representation of program options provides a "road map" for ASSESS which summarizes the functional capabilities of a program. You may explore the hierarchy of options by traversing the menu tree and reading the descriptive messages which appear at the bottom of each screen.

2.2.4 *ASSESS Screens and Menus*

ASSESS initially displays an introduction screen. Upon pressing any key, the first interactive screen is displayed. The information entered or displayed on the succeeding three screens, namely the "Data Quality Objectives" screen, the "Sampling Considerations" screen and the "Historical Assessment" screen, are used presently for information purposes. No calculations are performed using the information from these three screens. The information is written to a user-specified file, along with the results of other calculations.

Figure 2-2

The Menu Hierarchy



Section 3

Using ASSESS in an Assessment Study: Example

3.1 OVERVIEW

This section will demonstrate how to use the ASSESS software to conduct an assessment study. We start with an example data set obtained from an actual Superfund site which was contaminated by lead deposition from a smelter; however, the arrangement of the data into batches and data from field evaluation samples are fictional and are included for illustrative purposes. Through this example data set, we will explore the ASSESS utilities and analyze its results. Two other data sets for the alternative QA design will also be shown. The data set "standard.fil" has been included with the software, so that you may repeat the exercise as a tutorial or to test the software. For a detailed explanation of the data, refer to the "Rationale document"(1).

The pilot study was conducted over a representative area to determine spatial variability and extent of the lead contamination in order to develop an efficient sampling network for obtaining representative measurements of contamination over a large area. The quality assessment program was implemented to assess variability from the collection, handling, and analysis of the samples.

The "standard.fil" data set is an ASCII file in the ASSESS format. It contains data grouped into 23 batches. The file structure is described in Section 2. The first few lines of data without the historical information are as follows:

```
1  -9999.000  -9999.000  -9999.000  448.000  505.000  -9999.000 -9999.000
2  -9999.000  -9999.000  -9999.000  475.000  488.000  -9999.000 -9999.000
3  -9999.000  -9999.000  -9999.000  423.000  424.000  -9999.000 -9999.000
4    389.000  -9999.000    430.000 -9999.000 -9999.000 -9999.000 -9999.000
```

Each row represents a batch. The first through the third rows indicate that only Field Evaluation Sample pairs (FES1 and FES2) exist, and all other samples are unknown (i.e., missing). The fourth batch indicates that only a routine sample (RS) and a preparation split sample (PS) exist.

Notice that the ASSESS data files for the regular design consist of the following columns in the given order: RS, FD, PS, FES1, FES2, ELES1, ELES2.

Assuming that you have already copied the software and data into a directory called ASSESS on your hard disk and have used the command "CD\ASSESS" to access the directory, you can run ASSESS by typing the command:

```
ASSESS <enter>.
```

When the program begins execution, it first displays a screen with introductory information. When you press a key to proceed, you will see the program main screen and menu as displayed in Figure 2-1.

The bottom line on the screen provides the list of available options. The first three options move you to an area on the screen (or to a new screen) where you can input or select program parameters.

We begin by running through the program using the menu options.

Throughout this tutorial you will see the phrase "select an option" used often. You "select" an option by positioning the cursor bar on the option or field, and pressing the <enter> key.

In the data analysis section of this document the following points are noted:

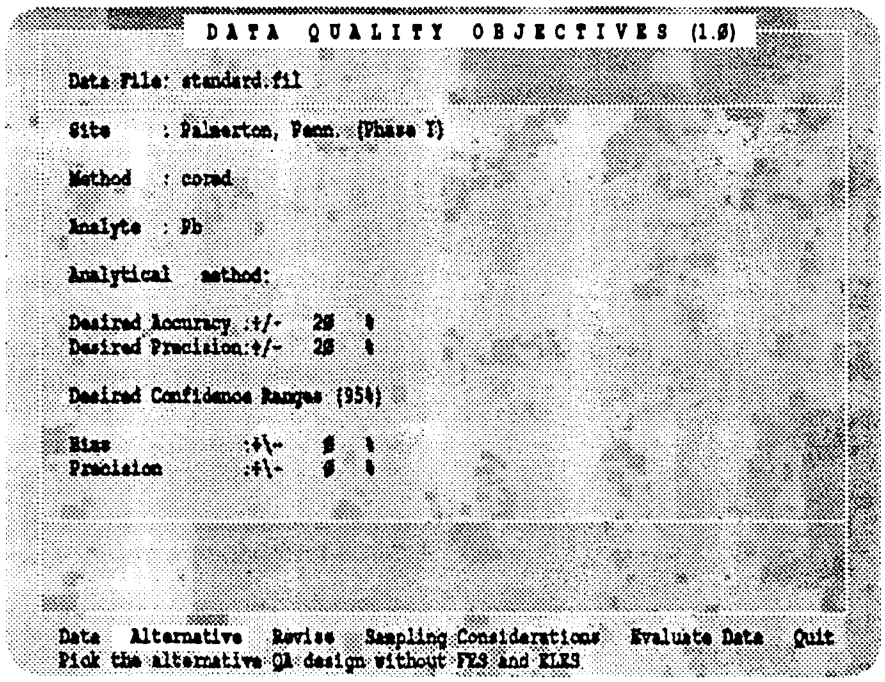
1. The line **"Insufficient samples exist for this variance"** for any error variance estimates means that enough samples do not exist to assess the variance.
2. If the value of any variance estimate is less than zero, a value of zero will be assigned to that variance.

Data

The "Data" option is used to decide whether a data file is present or data is to be entered on the screen. Select the data option and answer Yes to the prompt "Do you want to specify a data file? (use <space> bar):". This is done by pressing the <enter> key on the toggle field "Yes". You are then asked about the format of the input file. Hit the space bar to toggle through the options, and select the "standard (with no labels)" field in response to the "What is the input file format? (use <space> bar):" prompt. As before, select a particular field by pressing the <enter> key. You are then prompted for a data file name. Notice the cursor jumps to the "Data file:" field on the screen. Type the name of the input data file, which in this case is "Standard.fil", and press the <enter> key. A short tuned noise will be generated, and the message "ERROR – data file not found (press any key)" will be displayed if an incorrect or a non-existent file is entered. In such a case, select the Data option and proceed with correct entries. The following screen will be displayed (Figure 3-1).

Figure 3-1

ASSESS Main Screen



Alternative

This option allows the user to select the alternative QA design without the FES and ELES values. Since the first example does not employ the alternative design, DO NOT select this option. Use your cursor keys to move to the "Revise" option.

Revise

This option is used to revise the screen parameters. Note that the parameters on the second part of the screen displaying the site, method, etc. are only for historical notations and have no bearing on the result of the analysis. Note also that the displayed information is the result of the input given in the file "standard.fil". You may proceed to the next option by not selecting the "Revise" option, thus accepting the listed parameters. However, for illustration purposes, select the "Revise" option, move the cursor key to the "Analyte:" field, and type in "lead" over "Pb" and press the <enter> key. Pressing the <enter> key till the end of the screen parameters or the <left arrow> key at any time, will take you back to the "Revise" option on the menu fields.

Sampling Considerations

This option displays the "Sampling Considerations" menu. It is designed only for historical notations, and is merely a summary of the contents of parts of the data file. DO NOT select this option yet. We will discuss this after examining the remaining options on the screen.

Evaluate Data

This option displays the "Evaluate Data" menu. Through this menu, ASSESS does all of its computing work. It computes and displays measurement error variances. It also performs data transformations, produces reports and plots data. This option may be selected immediately after the specification of data input type and will bypass the sampling consideration and historical assessment screens. Experienced users will select this option first if quick data evaluation is required, thus bypassing the historical screens.

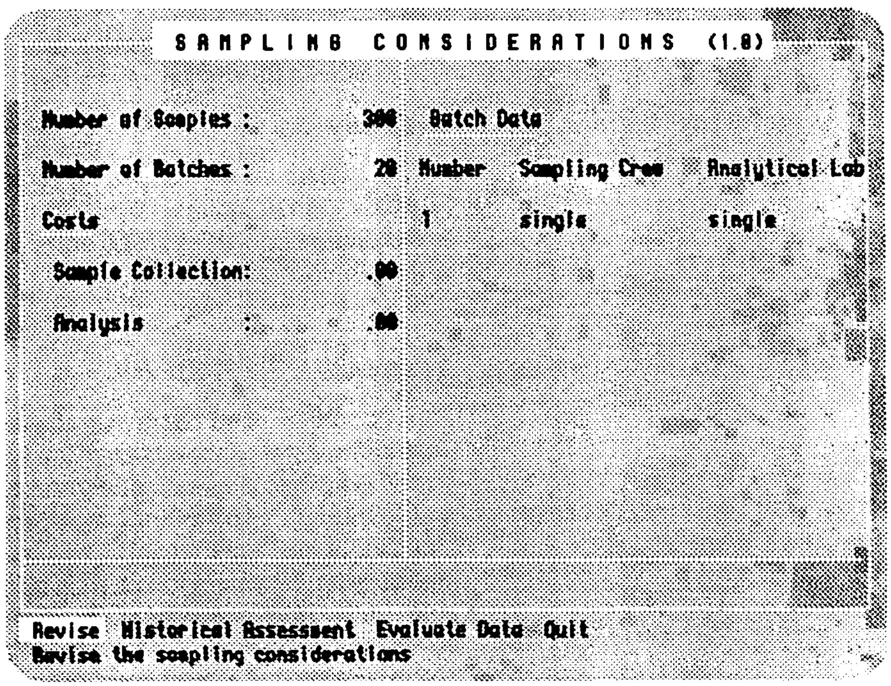
Quit

This option is used to exit the program. Using the analogy of the menu tree, the "Quit" option also allows you to "move up" one level in the tree. The "Quit" option will also appear in other successive screens. When this option is used from the main menu of the program, a Yes/No prompt is issued: "Do you really want to quit <Y/N>?". The <Q> key is typically used to select this option. The Yes/No prompt is a means of ensuring that a series of <Q> keystrokes will not cause inadvertent termination of the program.

You may now select the "Sampling Considerations" option from the menu bar. The following screen will be displayed:

Figure 3-2

Sampling Considerations



We will now discuss the options accessed through this screen.

Revise

This option is exactly similar to the discussion of the "Revise" option above. Let us change the analysis cost to $500.00. Select the "Revise" option, use the <down arrow> key to move to the "Analysis" field, and type 500.00. Notice that if you hit an <enter> key after entering the number 500.00, you will be placed into the next part of the screen regarding the batch data. To get back to the "Revise" option, move your cursor bar to the extreme left or right sides of the screen frame using the arrow keys.

Historical Assessment

This option displays the "Historical Assessment" menu. This menu shows a screen with the bias and measurement data of the input data file. DO NOT select this option yet. We will discuss it after examining the remaining options on the screen.

Evaluate Data

This option is exactly similar to the option discussed for the main screen.

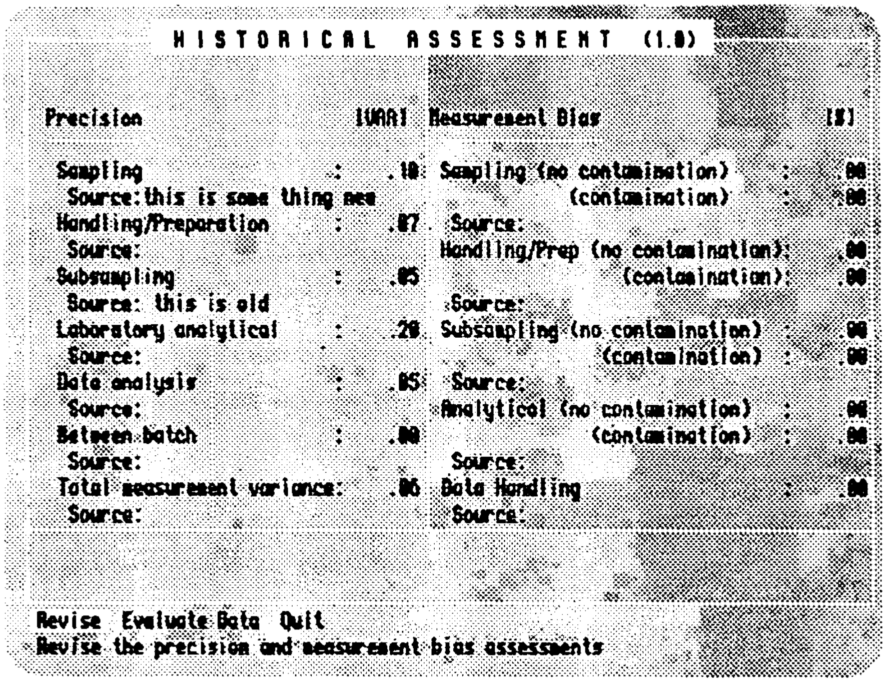
Quit

This option will return the user to the main menu of the main screen.

We may now select the "Historical Assessment" option. After pressing the <enter> key on the "Historical Assessment" option, the following screen will be displayed.

Figure 3-3

Historical Assessment Screen



We will now discuss the options accessed through this screen.

Revise

Through this option, you may alter any of the screen fields as discussed in the previous explanation of Revise. Select the "Revise" option, and change the "Total Measurement Variance:" field to 0.09.

Evaluate Data

This option is essentially the same as previously discussed.

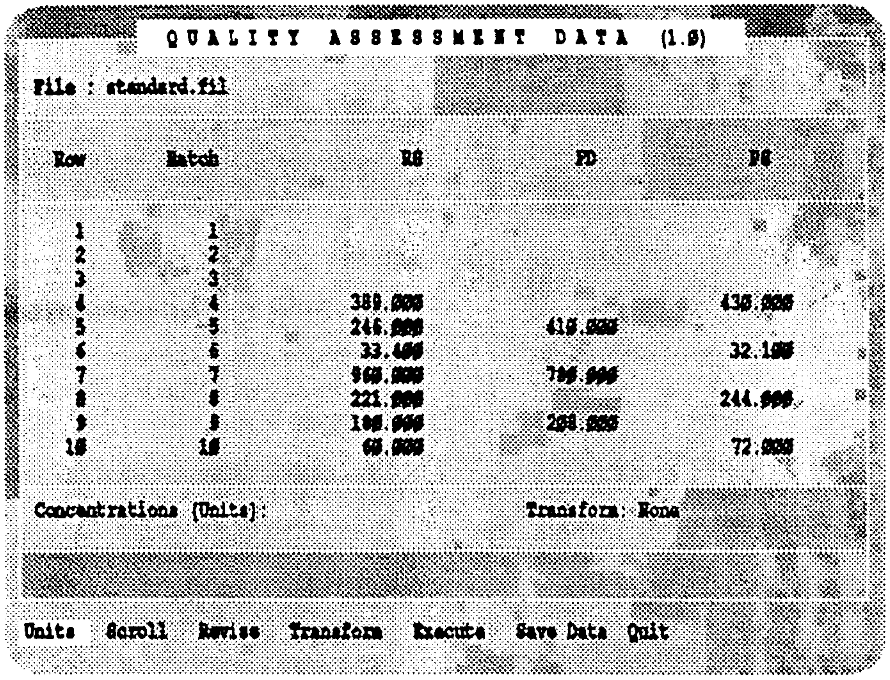
Quit

This option will return you to the previous menu which is the "Sampling Considerations" screen.

We will now select the "Evaluate Data" menu option to display the "Quality Assessment Data" screen.

Figure 3-4

Quality Assessment Data



The screen above shows the contents of your input data file. It only shows data for 10 batches within the RS, FD, and PS columns. The "Scroll" option described below will let you explore the additional batches and the remaining columns not seen on the screen.

We will now discuss the options accessed through this screen.

Units

This option will allow you to enter the concentration unit. Select this option and type "mg/kg". When you hit the <enter> key after typing in the concentration unit, you will be back on the units option.

Scroll

This option will allow you to scroll through the input screen. The data file "standard.fil" contains 23 batches, but only 10 are shown on the screen. Select the "Scroll" option. In the message frame, you will notice the message "Use <arrow> key to scroll or <Q> to Quit." As you push the <right arrow> key, you will notice that additional columns of input will appear on the screen. Note that missing values are represented by blanks on the screen, thus improving readability. The <down arrow> key will let you scroll and observe additional batches, if any. After scrolling through the screen, press the letter <Q> to get back to the "Scroll" option.

Revise

This option is the same as previously discussed. You may alter any of the input values by a sequence of arrow keys (to get to the correct position) and typing over the old values. Note that the "Save Data" option must be selected to save any new changes before proceeding to transformations of the data, or execution of the program. For the time being, do not alter any of the data. Proceed to the following option.

Transform

The Transform option is used as a tool to determine if the data needs to be transformed and to carry out various data transformations.

The "Transform" option plots a scattergram of the data. When the "Transform" option is selected, you will have a choice as to the type of data to be plotted. Select this option, and you will be prompted by "Specify plot of which concentration to use? (use <space> bar):". Toggle through the possible fields which are "RS&FD" and "RS&PS". Remember to use the space bar to toggle throughout the possible options. Select the "RS&FD" field and press the <enter> key. Note the message on the message line, and press any key to view the scattergram. The following is the plot of the original data (untransformed).

Figure 3-5

Scatter plot of the QA data

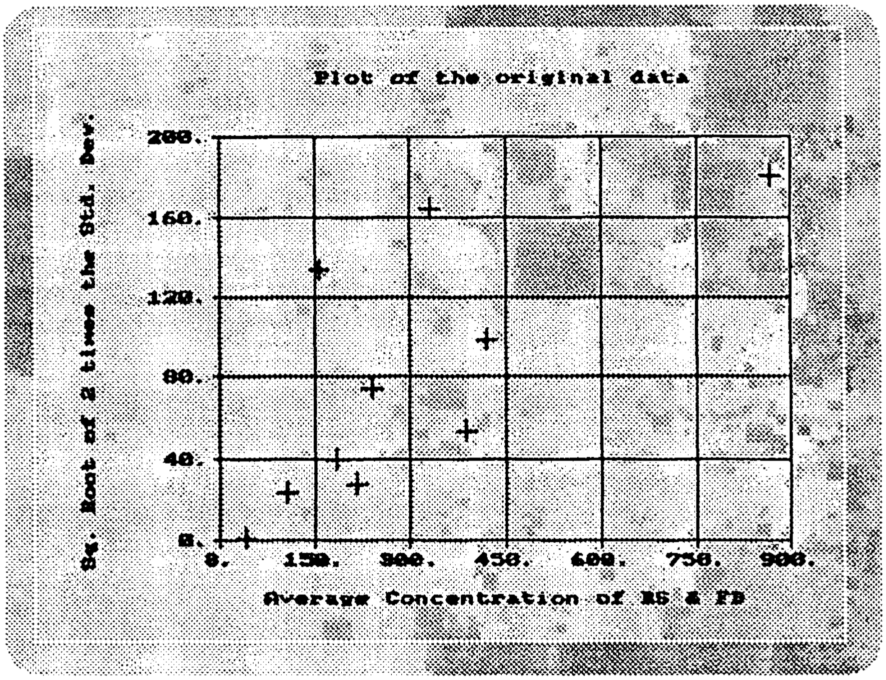
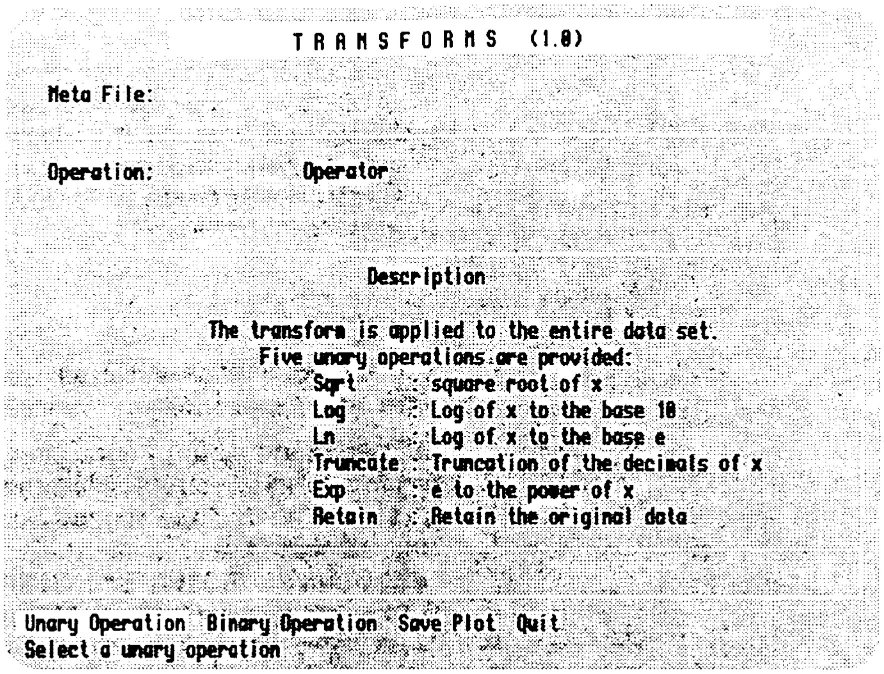


Figure 3-5 illustrates the need for a transform of the original data. The plot shows that the standard deviation of the data (multiplied by $\sqrt{2}$) from routine samples and field duplicates increases with the average concentration of these samples. A logarithmic transform of the data will stabilize the variance of the data over measured concentration range. After this transformation has occurred, the variances may be computed for the purpose of assessing variability throughout the measurement process.

Press the letter <Q> to quit the graph, and observe the following "Transforms" screen.

Figure 3-6

Transforms Screen

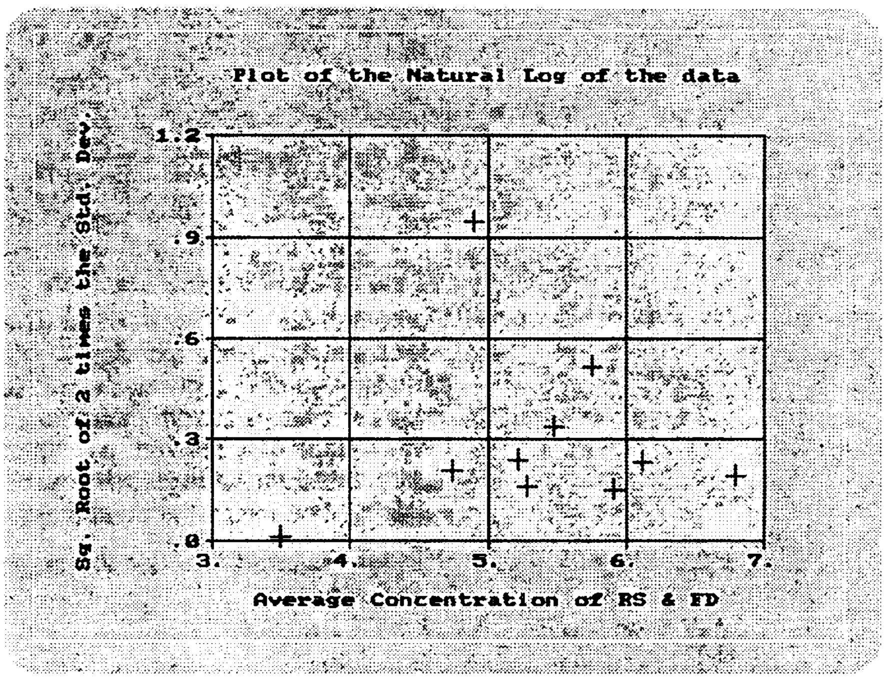


Unary Operation

This option allows the user to toggle through five unary operations, as well as a "Retain" option, which allows the original data to be retained thereby eliminating any confusion as to the type of data being transformed. These six options are also listed on the screen. Select the "Unary operation", and use the space bar to toggle through the possible selections. Select the "Ln" operator to take the log base e of the original data. After selecting this option you will remain in this screen. In order to view the newly created plot, select the "Quit" option. Notice the message at the bottom of the screen when the cursor bar is moved to the "Quit" option. This option will return you to the "Quality Assessment Data" screen. Notice the data displayed on the screen. The values are log base e of the original data. Select the "Transform" option and the "RS&FD" toggle field. Press <enter> to view the following graph:

Figure 3-7

The Scatter Plot of the Log Transformed Data



The data now fall along a straight horizontal line. The variance of the data is now said to be "stabilized".

Press the letter <Q>, and select the "Quit" option to return to the "Quality Assessment Data" screen. Notice that the screen shows the log-transformed data of the input data.

In order to explore the remaining options of the "Transforms" menu, select the "Transform" option. Select the "RS & PS" toggle field and view the graph. Press the letter <Q> to quit the graph and enter the "Transform" screen. The "Unary Operation" option was discussed above. It may be used to retain the original data, so that additional transforms may be applied to the untransformed data.

Binary Operation

This option allows data transformation using the given binary operators on the screen. This option has the same features as the "Unary Operation" option, and allows you to perform multiplication, division, addition, subtraction, exponentiation, and retain the original data.

Save Plot

This option saves the generated plot through the "Transform" option. The plot that will be saved is the plot just observed prior to reaching this screen layout. Conceptually, it saves the plot that is no longer visible by the user, though it still exists. In order to save the plot just viewed, select this option and enter "Scatter.met" for the "Meta File:" prompt.

Quit

This option will return to the "Quality Assessment Data" screen. Select this option to return to the "Quality Assessment Data" screen.

Execute

This option will display the results obtained by applying the equations in table 5 of the "Rationale Document"(1). The primary purpose here is to estimate measurement-error variance components. The measured lead concentrations in soil (in mg/kg) are given for 10 Preparation Split (PS) pairs and for 10 Field Duplicate (FD) pairs. The amount of data used has been kept small for readability and to illustrate the use of the computer program to calculate variances. Select the "Execute" option. The following screen will be displayed:

Figure 3-8

The Results Screen

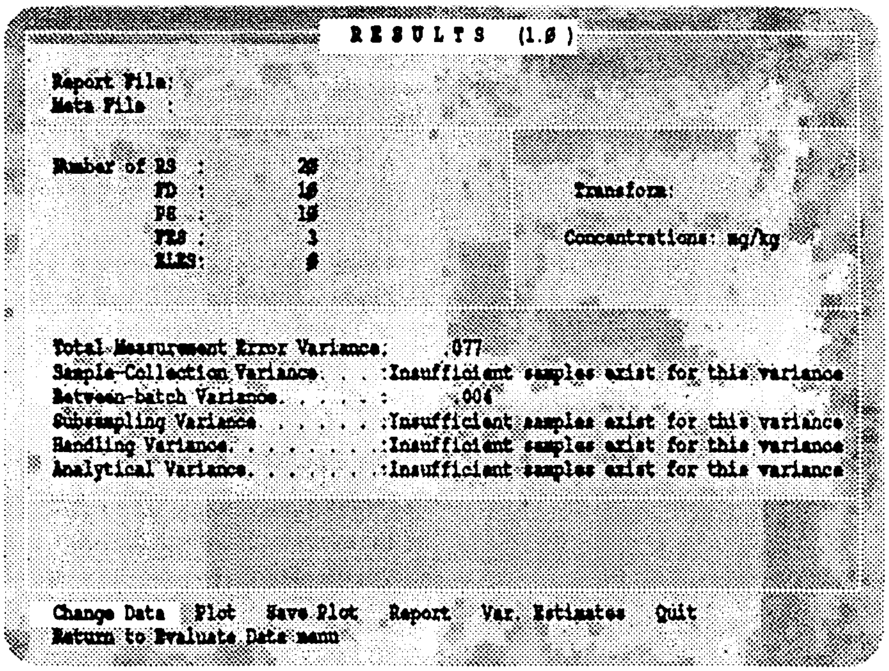


Figure 3-8 shows a summary of the results. Note that when enough samples do not exist to assess any of the variances, "Insufficient samples exist for this variance" will be displayed. For example, sample-collection variance can not be calculated, because the error estimate calculated from external laboratory evaluation samples (ELES) does not exist. Refer to Table 5 of the "Rationale Document"(1) for the formulas. Also note that the analytical variance could not be computed, since the estimate from external laboratory evaluation samples (ELES pairs) can not be obtained. This screen also displays a summary of the number of QA samples present. Note that the number of ELES values is equal to zero.

The options on this screen will now be discussed.

Change Data

This option will return the user to the "Evaluate Data" menu to make additional changes. The user will examine the result on the screen and decide if changes are necessary. This option will not do anything computationally, but is only a means for accessing the data screen. You may select this option, if there is a need for additional changes. This option will take you back to the "Quality Assessment Data" screen. After making changes, the "Execute" option will bring you back to the "Results" screen. This option will be selected after explaining the following options.

Var. Estimates

This option will display a screen showing the values of various variance estimates. Select the "Var. Estimates" option. The following screen will be displayed.

Figure 3-9

The Intermediate Results Screen

A table of the variance estimates

Field Duplicates (SFD). . . . . :	.073
Preparation Splits (SPS). . . . :	.005
Field Evaluation Samples (SWFES):	.001
Field Evaluation Samples (SBFES):	.010
External Lab Eval. Samp. (SWLES):	.000

Press any key to continue

The table shows the variance estimates given in Table 5 of the "Rationale Document"(1). Press any key to return to the "Results" screen.

Plot

This option is used to display a plot of the error bar graph. (Note the message on the message line.) Select the "Plot" option, and press any key to view the following plot.

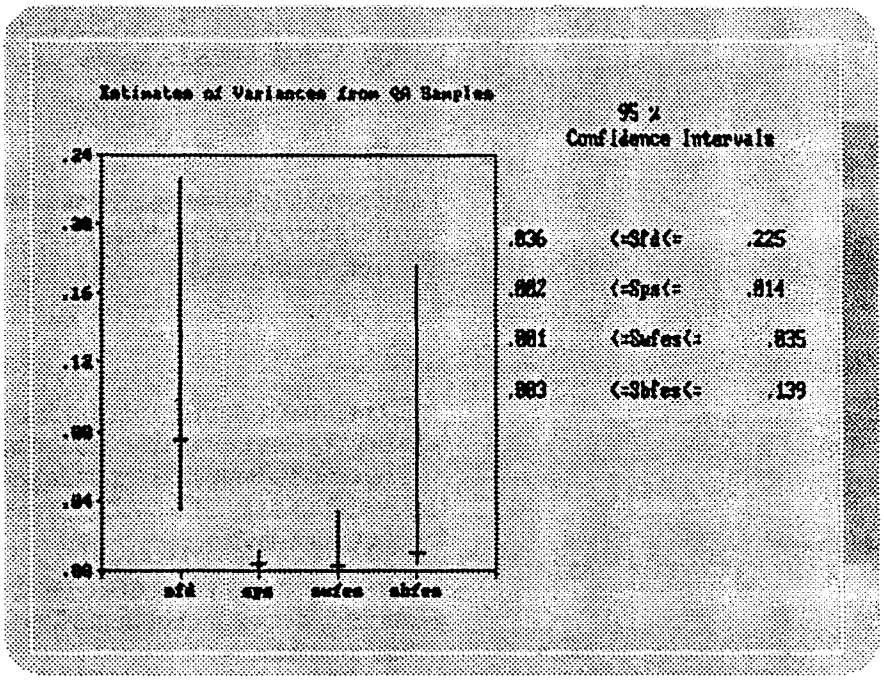


Figure 3-10

The Error Bar Graph

The plot illustrates the range in which the estimates of the various variance components may be expected to occur within a 95% confidence interval. It is clear from the length of the line for "sbfes" (Field Evaluation Samples estimate) that greater use of field evaluation samples would have improved the assessment of between-batch variability, as well as total measurement error variance. Table 3 of the "Rationale Document"(1) is used to determine the 95% confidence intervals for variances based on the degrees of freedom. Press the letter <Q> to return to the "Results" screen.

Save Plot

This option saves the error bar chart of the plot just viewed. Select this option, and type in "barchart.met" in response to the "Meta File:" prompt. After the metacode file has been written, press any key to return to the menu bar. A Metacode file is a device-independent file used by the program HPPLOT to produce a hardcopy of the plot on an HP plotter. Notice that you may also press the letter <P> to produce a hardcopy of the plot (Make sure that the printer is on-line). For more information on how to port this file into WordPerfect, refer to section 1.5.2, and consult your WordPerfect manuals.

Report

This option generates a report of the data and its results in three formats. The output may go to a file with input format, a file with report format, and to the printer. Select this option and select the "file (report format)" toggle field. Type in "results.fil" after the "Report File:" prompt.

Quit

This option will return the user to the main menu.

In order to return to the "Evaluate Data" menu, select the "Change Data" option. You are now located at the "Quality Assessment Data" screen.

Save Data

This option allows the user to save the contents of the screen in a data file with the input format. Select this option, and type in "Saved1.fil" in response to the "File:" prompt.

Quit

This option will return the user to the main menu. This is a good time to take a break. Select the "Quit" option of the "Quality Assessment Data" screen. The resulting screen is the main screen of ASSESS. Select the "Quit" option to end this session of ASSESS. We will return to ASSESS to demonstrate input from keyboard.

Now the basic concept of ASSESS has been studied, two shorter examples dealing with input data from the keyboard and using alternative QA design will be offered.

As discussed earlier, the second and third screens in ASSESS are used in reviewing or revising the historical data. These two screens may be skipped without any effects on the computational aspect of ASSESS. In this example, we will allow the user to access the "Evaluate Data" menu, input pair data, carry out computations and sketch plots, and finally save input data at any time during the calculation phase. Obtain a hardcopy of the file "smdata.fil". The data in this file will be used as input to the program. At the DOS prompt in the appropriate subdirectory, type the command:

ASSESS <enter>

After observing the introductory screen, the screen of Figure 3-1 will be displayed. In the previous section, the sequence of actions needed to display various results were explained in a long-hand notation, where every keystroke was thoroughly explained.

To simplify our explanations, an abbreviated notation for the sequence of events will be used. A general formula exists for each option: Initiate the option, then take one or more actions, each of which may result in a screen field taking a particular value.

In order to get to the "Evaluate Data" menu, without a data file, use the following set of actions:

Option	Action	Field	Value
Data	Enter	Data File	No
Evaluate Data	Enter	Number of Rows	13
Revise	Enter		

Enter the values from the file "smdata.fil" using the <arrow keys> to move the cursor bar. Notice that the first 42 lines are historical information and will be ignored. You may pass over a field, thus assigning a missing value to that particular field ("-9999.0" in the data file represents a missing value).

Notice that by pressing the <enter> key, you will be positioned at the "Revise" option on the menu bar. Select it again to return to the input screen. Once all of the data is entered, take the following actions.

Option	Action	Field	Value
Save Data	Enter	Data file	Saved2.fil
Execute	Enter		

The screen of Figure 3-11 will be displayed. Notice that through the "Save Data" option, you may save your data at any time. The format of this file is "Input (with labels)". This point is important if you would want to use this file again to add or delete information. Therefore, on the first screen, you would select the "Input (with labels)" toggle field of the Data Option, if there is a need to use this file as input to ASSESS. This example is used to verify your results. Analysis of data is similar to the analysis discussed in the previous section.

Quit	Enter		
Quit	Enter	Quit Prompt	Y

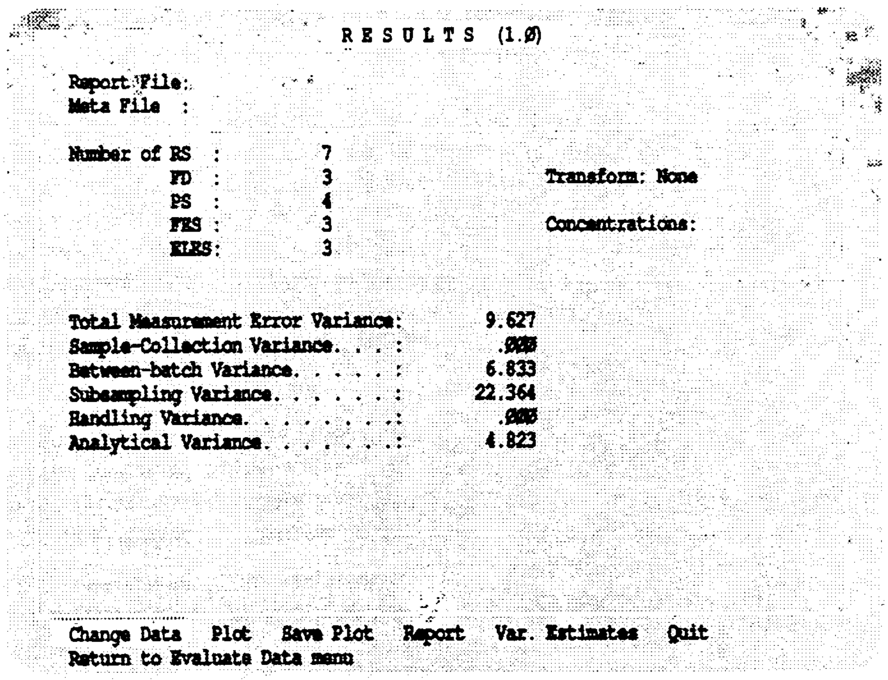


Figure 3-11

The Results Screen

The alternative QA design was developed to assess measurement error variances in absence of FES and ELES pairs. Formulas in Table 6 in the "Rationale Document"(1) are used to calculate the results. The required data for the alternative design are RS, FD, PS, BFD (Batch Field Duplicates), the location of BFD values, and FES1, and ELES1 values. The FES1 and ELES1 values are not used in the computations and are only used to represent bias. Note: ASSESS presently does not calculate bias in the data.

In the following example the data file "Alt1.fil" is used to illustrate the case where batch field duplicates are all obtained from one sampling location. The format of the file "Alt1.fil" is the same as for the data file "standard.fil". Take the following sequence of actions to display the variance estimates, produce error bar graphs and scattergrams.

Option	Action	Field	Value
Data	Enter	Data File	Yes, Standard (with no labels), Alt1.fil
Alternative	Enter	Sample Location	Yes, No

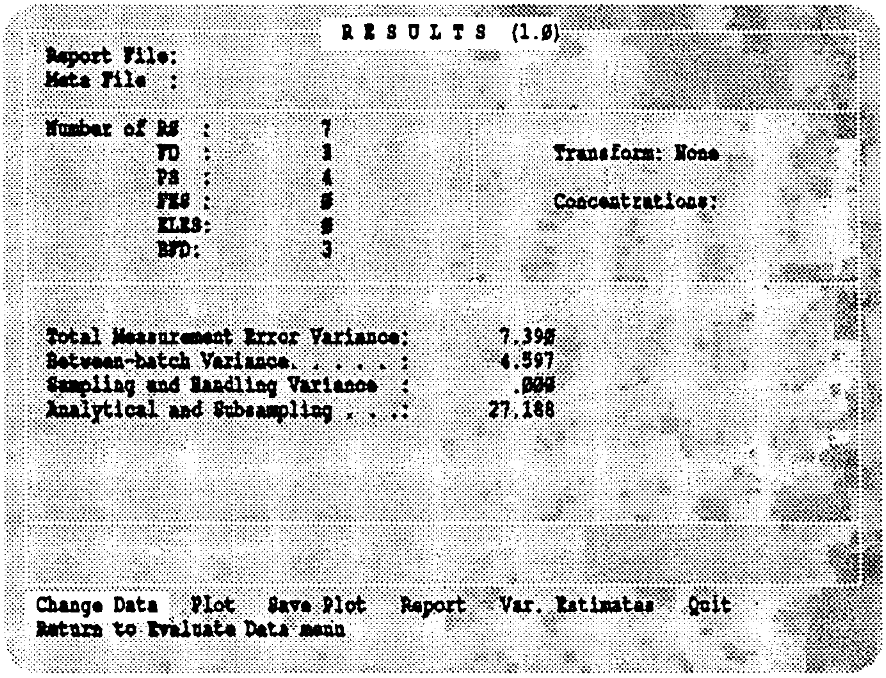
If you answer either "Yes" to both questions or "No" to both, you will be notified by an error message asking you to start over. Cursor bar returns to "Data" option.

Evaluate Data	Enter
Execute	Enter

The following screen will be displayed.

Figure 3-12

Alternative Design Results Screen



Note that the variance component associated with handling cannot be separated from that associated with sample collection, and that the variance component associated with subsampling cannot be separated from that associated with analysis. This loss of information is a consequence of not using FES and ELES values in the study. The sampling and handling variance is equal to zero. This variance is the result of subtracting the error estimate for the preparation splits s^2_{ps} from the error estimate for the field duplicates.

$$\sigma^2_h + \sigma^2_s = \sigma^2_{fd} - \sigma^2_{ps}$$

For this example

$$\sigma^2_h + \sigma^2_s = 2.793 - 27.188 = -24.395$$

ASSESS will report a value of zero, when the measured variance is a negative number. Follow the sequence of keystrokes:

Option	Action
Plot	Enter

The resulting graph is displayed in Figure 3-13.

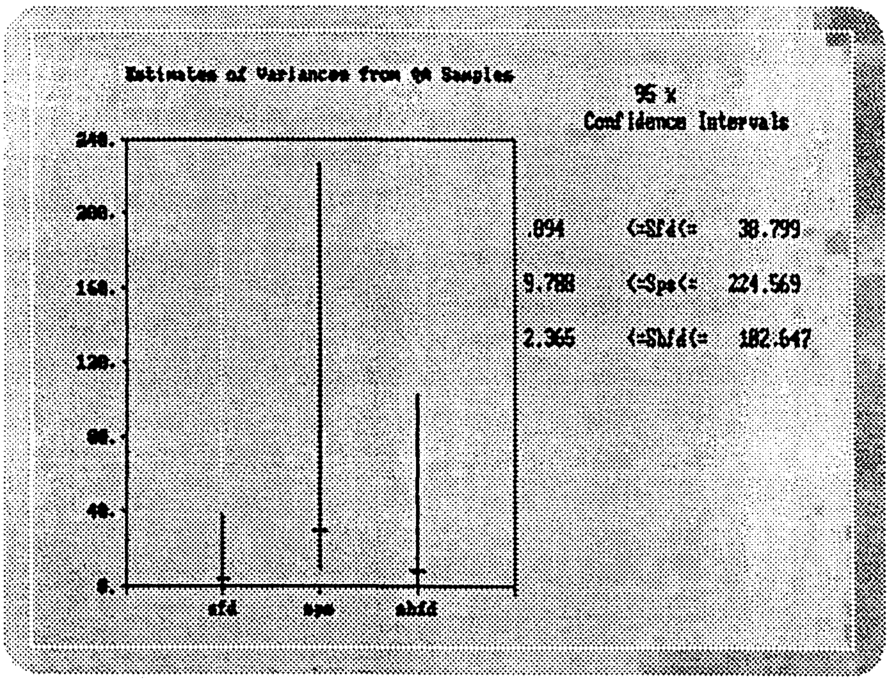


Figure 3-13

Alternative Design Error Bar Graph

Notice the large confidence interval for the preparation split samples. Perhaps more preparation split samples could be taken to reduce this large interval.

Option	Action
<Q>	Enter
Var. Estimates	Enter
Press any key	Enter

The resulting table is displayed in Figure 3-14.

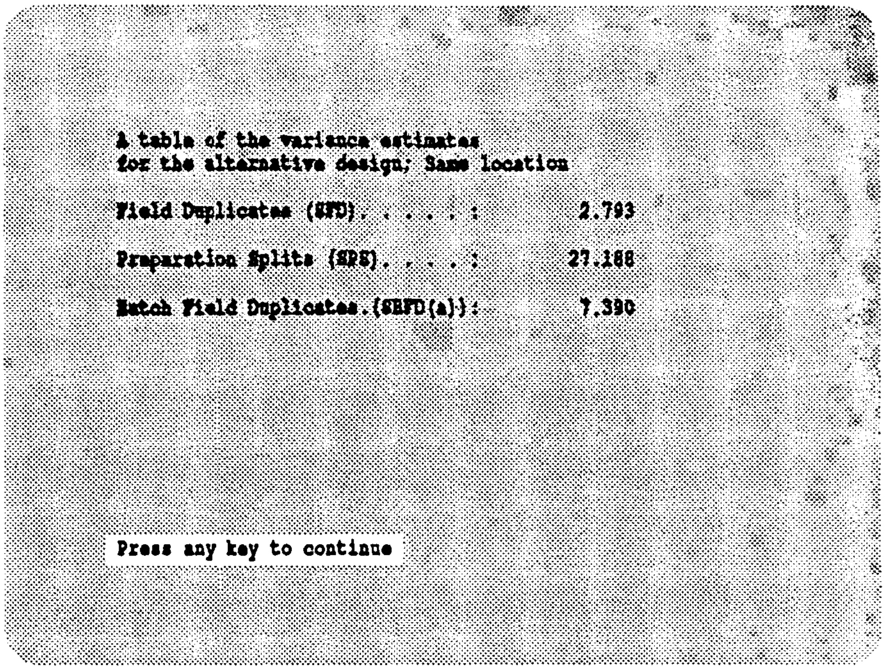


Figure 3-14

Variance estimates for the Alternative Design

The displayed data in this figure is a summary of the computed error estimates for the alternative design. Note that the estimate for the batch field duplicates is the one computed for condition (a). This condition is appropriate when the batch field duplicates are all taken from one sampling location.

You may end this session by the following given keystrokes or proceed with the data transformation as previously discussed.

Option	Action	Field	Value
Press any key	Enter		
<Q>	Enter		
<Q>	Enter	Prompt	Yes

The file "Alt2.fil" is also included in the distribution diskette. This file contains data necessary to carry out the alternative design where Field Duplicate Samples are taken from different locations. Table (6) of the "Rationale Document"(1) is used for the calculations. Note that for this design the error estimate for batch field duplicate (s^2_{BFD}) is calculated using the equation denotated for part (b).

Appendix A

Data Files

The data files are simple ASCII text files which may be created with any text editor, and can be printed using the DOS print command. ASSESS can produce two types of output files; both of which contain the historical information (for notational purposes only) displayed on the screens, the summary of results, and the quality assessment data. One of these output files can be read in as a data file by ASSESS (see "Example.fil", next page), whereas the other output file uses a report- like format (see Report of Results which follows) and is not readable by ASSESS. A third file (see "Standard.fil" which follows), produced only by the user, is readable by ASSESS but lacks the descriptive labels included in the other two output files. The third file type is provided so that the user may edit an input file without having to enter all the data via ASSESS; (this method is faster in cases where the number of quality assessment data is large).

Two example data files are provided. As noted above "Example.fil" is an example of a file generated by ASSESS that can be used as an input file. When selecting the Data option in the Data Quality Objectives menu, a question appears asking which format to use. If the toggle "Input (with labels)" is chosen, then the file "Example.fil" may be selected. If the toggle "Standard (no labels)" is chosen, then the file "Standard.fil" may be selected.

An explanation of the formats used in "Example.fil", the reporting of results (report sent to the printer) and in "Standard.fil" follow.

Certain lines of historical information will have no information after the descriptive label. This is specific to the example at hand and not representative of data files in general.

"Example.fil" is a data file, created by ASSESS, that contains the computed variances as well as any historical information (for notational purposes) displayed on the screens. Quality assessment data is also included. This file is also an input data file; so if results and data changes are to be saved for later use, this file type should be created.

This file is generated by selecting the Report option of the Results screen menu and then selecting the option "File (input format)". The quality assessment data is listed at the end of the file. It includes "-9999" values which represent missing values (see the description in *Data File Example - "Standard.fil"* concerning the format for the quality assessment data, line 43). These "-9999" values permit ASSESS to read the data and convert the "-9999's" to empty fields.

Screen labels precede the entries, making the file self explanatory.

Figure A-1

Example.fil data file

```
DATA QUALITY OBJECTIVES
Site  :Palmerton, Penn. (Phase I)
Method              :cored
Analyte             :Pb
Analytical Method:

Desired Accuracy : +/-  20%
Desired Precision: +/-  20%
Desired Confidence Ranges (95%)
  Bias      : +/-   0%
  Precision: +/-   0%

SAMPLING CONSIDERATIONS
Number of Samples:     300
Batches          :      20
Costs for
  Sample Collection:        .00
  Analysis         :        .00


                Batch Data
Number    Sampling Crew       Analytical Lab
1         single              single
END OF BATCH DATA


HISTORICAL PRECISION ASSESSMENTS              [VAR]
sampling                                   :  .1000
source: this is some thing new
handling, transportation, preparation:        .0700
source:
subsampling                                :  .0500
source:  this is old
laboratory analytical                      :  .2000
source:
data analysis and interpretation           :  .0500
source:
between batch                              :  .0000
source:
TOTAL MEASUREMENT VARIANCE                 :  .0600
source:

HISTORICAL MEASUREMENT BIAS ASSESSMENTS        [%]
sample collection (no contamination)    :    .0000
sample collection (contamination)       :    .0000
source:
handling/preparation (no contamination):     .0000
handling/preparation (contamination)    :    .0000
source:
                                 -1-
```

```
subsampling (no contamination)          :    .0000
subsampling (contamination)             :    .0000
source:
analytical (no contamination)           :    .0000
analytical (contamination)              :    .0000
source:
data handling                           :    .0000
source

SUMMARY OF RESULTS
number of RS  :              20
number of FD  :              10
number of FS  :              10
number of FRS :               3
number of BLES:               0

Total Measurement Error Variance:     5638.338000
Sample-Collection Variance      :Insufficient number of samples
Between-batch Variance          :      748.083400
Subsampling Variance            :Insufficient number of samples
Handling Variance               :Insufficient number of samples

QUALITY EVALUATION DATA   Transform: None
                          Concentrations: mg/kg

Batch    RS         FD         FS         FRS1       FRS2       BLES1      BLES2
  1 -9999.000 -9999.000 -9999.000   448.000   505.000 -9999.000 -9999.000
  2 -9999.000 -9999.000 -9999.000   475.000   488.000 -9999.000 -9999.000
  3 -9999.000 -9999.000 -9999.000   423.000   424.000 -9999.000 -9999.000
  4   389.000 -9999.000   430.000 -9999.000 -9999.000 -9999.000 -9999.000
  5   246.000   410.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
  6    33.400 -9999.000    32.100 -9999.000 -9999.000 -9999.000 -9999.000
  7   960.000   780.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
  8   221.000 -9999.000   244.000 -9999.000 -9999.000 -9999.000 -9999.000
  9   180.000   208.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
 10    60.000 -9999.000    72.000 -9999.000 -9999.000 -9999.000 -9999.000
 11    87.000   221.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
 12   275.000 -9999.000   233.000 -9999.000 -9999.000 -9999.000 -9999.000
 13   349.000   400.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
 14   474.000 -9999.000   446.000 -9999.000 -9999.000 -9999.000 -9999.000
 15   478.000   382.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
 16    33.500 -9999.000    32.700 -9999.000 -9999.000 -9999.000 -9999.000
 17    33.000    33.300 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
 18  1360.000 -9999.000  1340.000 -9999.000 -9999.000 -9999.000 -9999.000
 19   104.000   128.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
 20   313.000 -9999.000   294.000 -9999.000 -9999.000 -9999.000 -9999.000
 21   201.000   161.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
 22    67.000 -9999.000    67.000 -9999.000 -9999.000 -9999.000 -9999.000
 23   275.000   199.000 -9999.000 -9999.000 -9999.000 -9999.000 -9999.000
                                 -2-
```

The report data file is created by ASSESS and contains the computed variances as well as any historical information displayed on the screens. Quality assessment data are also included. This file is the same as the "Example.fil" discussed in the preceding section with one exception: the quality assessment data has blanks where the "-9999" values were located. As a result this file cannot be used as an input data file.

This file is generated by selecting the Report option of the Results screen menu and then selecting the option "File (report format)". The file may be sent to the printer by selecting the" Printer " option.

Only the quality assessment data are shown below as the rest of the file is the same as "Example.fil" shown on the previous page. Note that the "-9999" values have been replaced with blanks.

Figure A-2

Report data file without the historical information

QUALITY EVALUATION DATA   Transform: None

Concentrations: mg/kg

Batch	RS	FD	PS	FRS1	FRS2	ELRS1	ELRS2
1				448.000	505.000		
2				475.000	488.000		
3				423.000	424.000		
4	389.000		430.000				
5	246.000	410.000					
6	33.400		32.100				
7	960.000	780.000					
8	221.000		244.000				
9	180.000	208.000					
10	60.000		72.000				
11	87.000	221.000					
12	275.000		233.000				
13	349.000	400.000					
14	474.000		446.000				
15	478.000	382.000					
16	33.500		32.700				
17	33.000	33.300					
18	1360.000		1340.000				
19	104.000	128.000					
20	313.000		294.000				
21	201.000	161.000					
22	67.000		67.000				
23	275.000	199.000					

"Standard.fil" is an input data file created by the user and stripped of any descriptive (screen) labels. ASSESS can read but cannot generate such a file. All entries must start in column 1. The number (e.g., '1.)') that appears on each line is used as a line number reference and does not appear in the actual file. For descriptions of each line, referenced by the line number, follow the example.

Figure A-3

Explanation of standard.fil data file

```
 1.)Palmerton, Penn. (Phase I)
 2.)cored
 3.)Pb
 4.)
 5.)20
 6.)20
 7.)0
 8.)0
 9.)300
10.)20
11.).00
12.).00
13.)1      single      single
14.)END OF BATCH DATA
15.).1000
16.)
17.).0700
18.)
19.).0500
20.)
21.).2000
22.)
23.).0500
24.)
25.).0000
26.)
27.).0600
28.)
29.).0000
30.).0000
31.)
32.).0000
33.).0000
34.)
35.).0000
36.).0000
37.)
38.).0000
39.).0000
40.)
41.).0000
42.)
43.) 1 -9999.000 -9999.000 -9999.000 448.000 505.000 -9999.000 -9999.000
44.) 2 -9999.000 -9999.000 -9999.000 475.000 488.000 -9999.000 -9999.000

                                   -1-
```

Descriptions: The descriptions are broken down into screens and include the screen label, type of field (A: Alphanumeric, I: Integer, F: Floating point), and length of field.

Figure A-4

Explanation of Standard.fil data file, continued

Descriptions:

Data Quality Objectives screen

1.) Site, A, 64
2.) Method, A, 14
3.) Analyte, A, 14
4.) Analytical Method, A, 14
5.) Desired Accuracy, I, 4
6.) Desired Precision, I, 4
7.) Bias, I, 4
8.) Precision, I, 4

Sampling Considerations screen

9.) Number of Samples, I, 10
10.) Number of Batches, I, 10
11.) Sample Collection, F, 10.2
12.) Analysis, F, 10.2

The following line is historical information about each batch of data. A maximum of 10 such lines is permitted. If more than 10 are present then the program will report an error in reading the data.

13.) Number, A, 7, Occupies columns 1-7.
13.) Sampling Crew, A, 15, Occupies columns 9-23.
13.) Analytical Lab, A, 15, Occupies columns 25-39.
14.) END OF BATCH DATA must appear. This tells Assess that the last line of batch data descriptions (eg. line 13) has been written. An "E" or "e" in the first column of this line is sufficient.

Historical Assessment screen

15.) Sampling, F, 6.4
16.) Source, A, 26
17.) Handling/Preparation, F, 6.4
18.) Source, A, 26
19.) Subsampling, F, 6.4
20.) Source, A, 26
21.) Laboratory analytical, F, 6.4
22.) Source, A, 26
23.) Data analysis, F, 6.4
24.) Source, A, 26
25.) Between batch, F, 6.4
26.) Source, A, 26
27.) Total measurement variance, F, 6.4
28.) Source, A, 26
29.) Sampling(no contamination), F, 6.4
30.) Sampling(contamination), F, 6.4
31.) Source, A, 26
32.) Handling/Prep (no contamination), F, 6.4

-2-

33.) Handling/Prep (contamination), F, 6.4
34.) Source, A, 26
35.) Subsampling (no contamination), F, 6.4
36.) Subsampling (contamination), F, 6.4
37.) Source, A, 26
38.) Analytical (no contamination), F, 6.4
39.) Analytical (contamination), F, 6.4
40.) Source, A, 26
41.) Data Handling, F, 6.4
42.) Source, A, 26

Quality Evaluation Data

43.) This is the first row of quality evaluation data. There are eight columns. The first column represents the batch number and is an integer. The remaining seven columns represent the routine subsample (RS), the field duplicate subsample (FD), the preparation split subsample (PS), the first field evaluation sample (FES1), the second evaluation sample (FES2), the first external laboratory evaluation sample (ELES1), and the second external laboratory evaluation sample (ELES2), respectively. All seven samples are floating point.

!!IMPORTANT!!

The -9999 represents an empty field. On line 43 of the above example only columns five and six have values other than -9999. This means that FES1 and FES2 have values of 448 and 505, respectively; and that RS, FD, PS, ELES1 and ELES2 have no values for that row. The -9999 must be entered in the column of the sample that has no value for that row. If it is not entered then Assess will either read the data incorrectly or will display an error message.

44.) Second row of quality evaluation data. A maximum of 1000 rows of such data may be entered.

-3-

Appendix B

Reference

(1) U.S. EPA. 1990. A Rationale for the Assessment of Errors in the Sampling of Soils. Environmental Monitoring Systems Laboratory, Las Vegas, Nevada. EPA/600/4-90/013.

Appendix C

Nomenmclature

RS	Routine sample
FD	Field duplicate
PS	Preparation split
FES1	Field evaluation sample 1
FES2	Field evaluation sample 2
ELES1	External laboratory evaluation sample 1
ELES2	External laboratory evaluation sample 2
BFD	Batch field duplicate
Location	Location of a batch field duplicate sample
s^2_{FD}	Field duplicates error estimate
s^2_{PS}	Preparation splits error estimate
s^2_{WFES}	Field evaluation samples error estimate within batches
s^2_{BFES}	Field evaluation samples error estimate between batches
s^2_{WLES}	External laboratory evaluation samples error estimate
s^2_{BFD}	Batch field duplicates error estimate
σ^2_m	Total measurement error variance
σ^2_s	Sampling error variance
σ^2_b	Between-batch variance
σ^2_{ss}	Subsampling variance
σ^2_h	Handling variance
σ^2_a	Analytical variance
$\sigma^2_s + \sigma^2_h$	Sampling and handling variance
$\sigma^2_a + \sigma^2_{ss}$	Analytical and subsampling variance
n	Number of sample pairs
m	Number of batch field duplicate samples
L	Number of sample locations for the alternative design

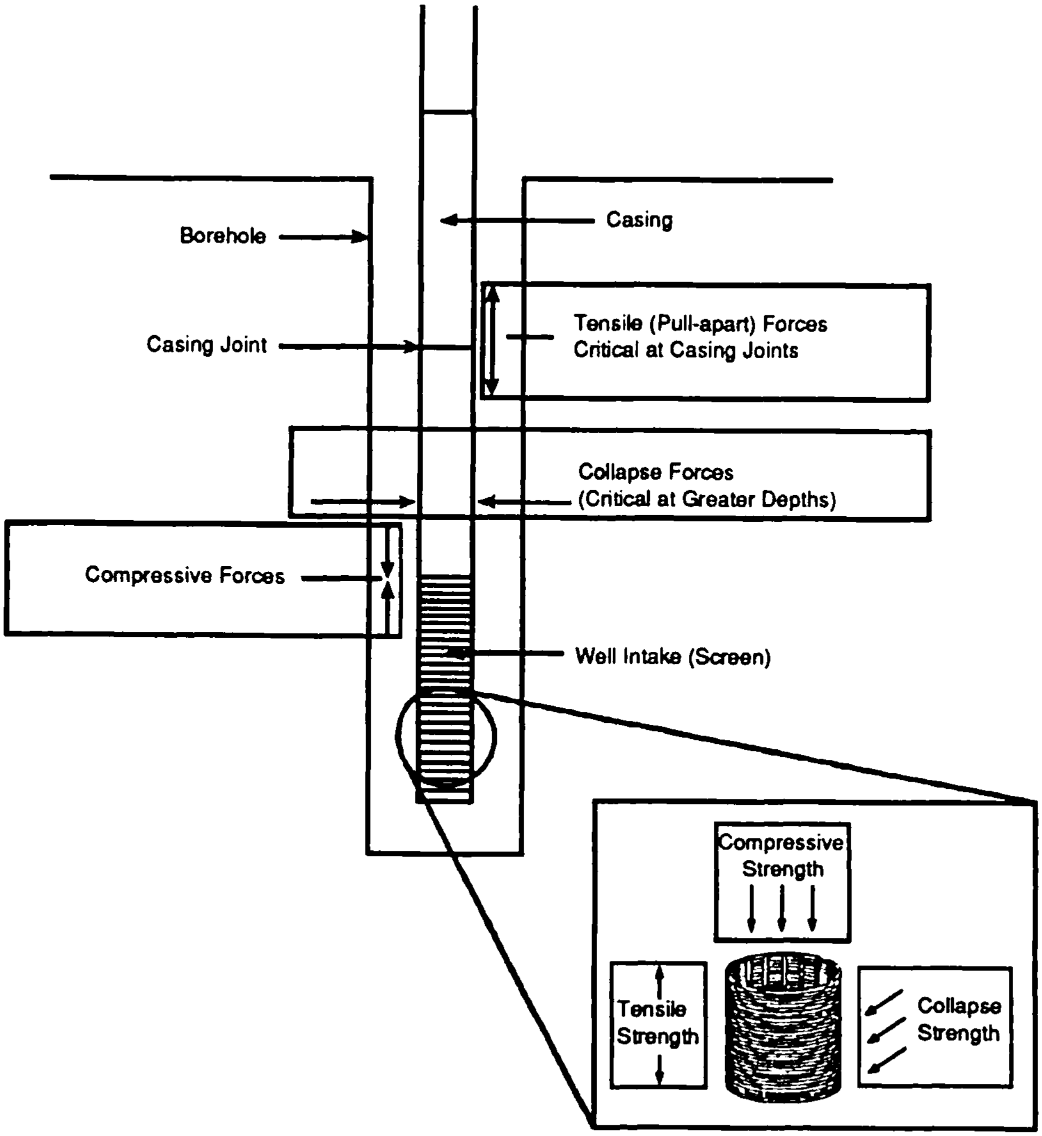
United States
Environmental Protection
Agency

Office of Research and
Development
Washington DC 20460

EPA/600/4-89/034
March 1991

EPA

Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells



EPA/600/4-89/034
March 1991

Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells

by:

Linda Aller, Truman W. Bennett and Glen Hackett
Bennett & Williams, Inc.
Columbus, Ohio 43231

Rebecca J. Petty
Ohio Department of Natural Resources
Division of Groundwater
Columbus, Ohio 43215

Jay H. Lehr and Helen Sedoris
National Water Well Association
Dublin, Ohio 43017

David M. Nielsen
Blasland, Bouck and Lee
Westerville, Ohio 43081

Jane E. Denne **(also the Project Officer)**
Advanced Monitoring Systems Division
Environmental Monitoring Systems Laboratory
Las Vegas, Nevada 89193-3478

Environmental Monitoring Systems Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Las Vegas, Nevada 89193-3478

Printed on Recycled Paper

Notice

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Cooperative Agreement Number CR-812350-01 to the National Water Well Association. It has been subjected to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This document has been prepared in cooperation with EMSL-LV, Office of Research and Development. It is intended to be used as a general reference and will not supersede program-specific guidance (e.g., the RCRA Ground-Water Monitoring Technical Enforcement Guidance Document).

Abstract

The *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells* is intended to assist personnel involved with the design, construction, and installation of ground-water monitoring wells. This document does not focus on specific regulatory requirements, but instead presents state-of-the-art technology that may be applied in diverse hydrogeologic situations. The "Handbook" addresses field-oriented practices to solve monitoring well construction problems rather than conceptual or idealized practices. The information in this "Handbook" is presented in both matrix and text form. The matrices use a relative numerical rating scheme to guide the user toward appropriate drilling technologies for particular monitoring situations. The text provides the narrative overview of the criteria that influence ground-water monitoring well design and construction in various hydrogeologic settings.

The "Handbook" addresses topics ranging from initial planning for a monitoring well to abandonment. Factors influencing monitoring well design and installation include: purpose, location, site hydrogeology, contaminant characteristics, anthropogenic activities, and testing equipment that the well must accommodate. Decontamination procedures should be planned and executed with care. Detailed recordkeeping from the time of well installation through sampling to abandonment is very important. Numerous drilling and formation sampling techniques are available, and many factors must be considered in selecting an appropriate method. Materials for well casing, screen, filter pack, and annular sealants also should be selected and installed carefully. Well completion and development procedures should allow collection of representative ground-water samples and levels. Maintenance of monitoring wells is an important network management consideration. Well abandonment procedures should include consideration of the monitoring well construction, hydrogeology, and contamination at the site. The "Handbook" serves as a general reference for the numerous factors involved in monitoring well design, construction, and installation.

This report was submitted in fulfillment of Cooperative Agreement Number CR-812350-01 by the National Water Well Association under sponsorship of the Environmental Monitoring Systems Laboratory, Las Vegas, Nevada. This report covers a period from June 1985 to May 1989, and work was completed as of June 1989.

Contents

Figures

Tables

Acknowledgments

This document presents a discussion of the design and installation of ground-water monitoring wells without specific regulatory recommendations. The information contained within the document is the product of many experiences, both published and unpublished to date. Assisting in the direction of the project and in the review of various stages of the document was an able and knowledgeable advisory committee. Although each of the individuals contributed positively, this document is a product of the authors and may not be entirely endorsed by each of the committee members. To the following named persons, grateful acknowledgment of their contribution is made:

Roger Anzzolin, U.S. EPA, Office of Drinking Water
George Dixon, formerly with U.S. EPA, Office of Solid Waste
Tyler Gass, Blasland & Bouck Engineers, P.C.
James Gibb, Geraghty & Miller, Inc.
Todd Giddings, Todd Giddings & Associates
Kenneth Jennings, U.S. EPA, Office of Waste Programs Enforcement
Thomas Johnson, Levine-Fricke, Inc.
Ken McGill, formerly with U.S. EPA, Region 3
John Mann, formerly with U.S. EPA, Region 4
Roy Murphy, U.S. Pollution Control, Inc.
Marion R. Scalf, U.S. EPA, Robert S. Kerr Environmental Research Laboratory
Dick Young, U.S. EPA, Region 7
John Zannos, U.S. EPA, Region 1

The basic conceptual foundation for this report was supported in its infant stages by Leslie G. McMillion, U.S. EPA, retired. A special note of acknowledgment and gratitude is extended to him for his inspiration and support in starting this document.

In addition to the committee members, many individuals assisted in adding practical and regional perspectives to the document by participating in regional group interviews on many aspects of monitoring well design and installation. Thanks are also extended to the following individuals for the donation of their time and invaluable input:

John Baker, Anderson Geotechnical Consultants, Inc., California
Dala Bowlin, Jim Winneck, Inc., Oklahoma
John Braden, Braden Pump and Well Service, Mississippi
Harry Brown, Brown Drilling Company, Inc., Michigan
Kathryn Davies, U.S. EPA, Region 3
Hank Davis, Mobile Drilling, California
Tim De La Grange, De La Grange and Sons, California
Lauren Evans, Arizona Department of Health Services, Arizona
Jerry Frick, Walkerville Well Drilling and Supply Co., Michigan
Tyler Gass, Blasland & Bouck Engineers, P.C., New York
Jim Hendry, National Water Well Association, Ohio
Tom Holdrege, Anderson Geotechnical Consultants, Inc., California
Joseph Keely, Oregon Graduate Center, Oregon
Larry Krall, Layne Environmental Services, Arizona
Bruce Kroecker, Layne Environmental Services, Kansas
David Lang, U.S. EPA, Region 1

Bill Long, Jim Winneck, Inc., Oklahoma
Carl Mason, C.M. Consulting, Pennsylvania
Bill McKinnel, West Corp., Wyoming
Bruce Niermeyer, Interstate Soil Sampling, Inc., California
Harry Ridgell, Jr., Coast Water Well Service, Inc., Mississippi
Charles O. Riggs, Central Mine Equipment Co., Missouri
Scott Sharp, Layne Environmental Services, Arizona
Bill Snyder, William Stothoff Company, Inc., New Jersey
Steve Story, Layne Environmental Services, California
Fred Strauss, Layne Environmental Services, California
Dave Sullivan, D.P. Sullivan & Daughters Drilling Firm, Inc., Massachusetts
Bud Thorton, Associated Well Drillers, Inc., Idaho
Taylor Virdell, Virdell Drilling, Texas
Dick Willey, U.S. EPA, Region 1
Douglas Yeskis, U.S. EPA, Region 5
John Zannos, U.S. EPA, Region 1

In addition, gratitude is expressed to those individuals who participated in reviewing the document:

Joe Abe, U.S. EPA, Office of Solid Waste
Doug Bedinger, Environmental Research Center, UNLV
Regina Bochicchio, Desert Research Institute, UNLV
Jane Denne, U.S. EPA, EMSL - Las Vegas
Joe DLugosz, U.S. EPA, EMSL - Las Vegas
Phil Durgin, U.S. EPA, EMSL - Las Vegas
Larry Eccles, U.S. EPA, EMSL - Las Vegas
Steven Gardner, U.S. EPA, EMSL - Las Vegas
Jack Keeley, U.S. EPA, retired
Eric Koglin, U.S. EPA, EMSL - Las Vegas
Lowell Leach, U.S. EPA, Robert S. Kerr Environmental Research Laboratory, Ada
Wayne Pettyjohn, Oklahoma State University
Mario Salazar, U.S. EPA, Office of Drinking Water
Kenneth Scarbrough, U.S. EPA, EMSL - Las Vegas
Peter Siebach, U.S. EPA, Office of Solid Waste
Kendrick Taylor, Desert Research Institute, University of Nevada System, Reno
John Worlund, U.S. EPA, EMSL - Las Vegas

Kendrick Taylor also provided information contained in the borehole geophysical tool section of the document.

Section 1
Introduction

Objectives and Scope

The *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells* has been prepared as an aid to owners and operators of facilities as well as others concerned with proper installation of ground-water monitoring wells. This document is also designed to assist state and federal authorities in evaluating all aspects of monitoring well design and installation in varying hydrogeologic settings. Information contained within this publication does not address specific regulatory requirements, which must be followed, but rather presents state-of-the-art technology that can be used in differing situations.

This document is intended to be both informative and descriptive in nature. The objectives are to provide a concise description of the components of monitoring well design and installation and to detail the applicability of various drilling techniques in diverse hydrogeologic regimes. The information is presented in both text and matrix form. Through a relative numerical rating scheme, the matrix guides the user toward appropriate drilling technology for particular monitoring situations.

Impetus for the development of the *Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells* was provided by the passage of a series of federal laws which addressed the need to protect ground-water quality. Table 1 lists the laws enacted by Congress and summarizes the applicable ground-water activities associated with each law. Of the sixteen statutes listed in Table 1, ten statutes have regulatory programs which establish ground-water monitoring requirements for specific sources of contamination. Table 2 summarizes the objectives and monitoring provisions of the federal acts. While the principal objectives of the laws are to obtain background water-quality data and to evaluate whether or not ground water is being contaminated, the monitoring provisions contained within the laws vary significantly. Acts may mandate that ground-water monitoring *regulations* be adopted, or they may address the need for the establishment of *guidelines* to protect ground water. Further, some statutes specify the adoption of rules that must be implemented uniformly throughout the United States, while others authorize adoption of minimum standards that may be made more stringent by state or local regulations.

With such diverse statutes mandating ground-water monitoring requirements, it is not surprising that the regulations promulgated under the authority of the statutes also vary in scope and specificity. In general, most regulations further define the objectives of the statute and clarify the performance standards to achieve the stated objectives.

More specific ground-water monitoring recommendations can be found in the numerous guidance documents and directives issued by agencies responsible for implementation of the regulations. Examples of guidance documents include the Office of Waste Programs Enforcement Technical Enforcement Guidance Document (TEGD) (United States Environmental Protection Agency, 1986), the Office of Solid Waste Documents SW-846 (Wehran Engineering Corporation, 1977) and SW-611 (United States Environmental Protection Agency, 1987). The purpose of this "Handbook" is to be a general (non-program-specific) reference to provide the user with a practical decision-making guide for designing and installing monitoring wells, and it will not supersede program-specific guidance.

Purpose and Importance of Proper Ground-Water Monitoring Well Installation

The primary objective of a monitoring well is to provide an access point for measuring ground-water levels and to permit the procurement of ground-water samples that accurately represent in-situ ground-water conditions at the specific point of sampling. To achieve this objective, it is necessary to fulfill the following criteria:

1) construct the well with minimum disturbance to the formation;
2) construct the well of materials that are compatible with the anticipated geochemical and chemical environment;
3) properly complete the well in the desired zone;
4) adequately seal the well with materials that will not interfere with the collection of representative water-quality samples; and
5) sufficiently develop the well to remove any additives associated with drilling and provide unobstructed flow through the well.

In addition to appropriate construction details, the monitoring well must be designed in concert with the overall goals of the monitoring program. Key factors that must be considered include:

1) intended purpose of the well;
2) placement of the well to achieve accurate water levels and/or representative water-quality samples;
3) adequate well diameter to accommodate appropriate tools for well development, aquifer testing equipment and water-quality sampling devices; and
4) surface protection to assure no alteration of the structure or impairment of the data collected from the well.

Table 1. Summary of Federal Programs and Activities Related to the Protection of Ground-Water Quality (after Office of Technology Assessment, 1984)

Statutes	Investigations/detection: Inventories of sources[a]	Investigations/detection: Ambient ground-water monitoring	Investigations/detection: Ground-water monitoring related to sources[a]	Investigations/detection: Water supply monitoring	Correction: Federally funded remedial actions	Correction: Regulatory requirements for sources[a]	Prevention: Regulate chemical production	Prevention: Standards for new/existing sources[a]	Prevention: Aquifer protection	Prevention: Standards	Prevention: Other[b]
Atomic Energy Act			X		X	X		X		X	
Clean Water Act	X	X	X		X			X		X	X
Coastal Zone Management Act											X
Comprehensive Environmental Response, Compensation and Liability Act	X		X		X					X	
Federal Insecticide, Fungicide and Rodenticide Act			X				X	X			
Federal Land Policy and Management Act (and associated mining laws)			X					X			
Hazardous Liquid Pipeline Safety Act	X							X			
Hazardous Materials Transportation Act	X							X			
National Environmental Policy Act											X
Reclamation Act					X						
Resource Conservation and Recovery Act	X		X			X		X			
Safe Drinking Water Act	X		X	X				X	X	X	
Surface Mining Control and Reclamation Act			X		X			X			
Toxic Substances Control Act			X				X	X			
Uranium Mill Tailings Radiation Control Act			X		X	X		X			
Water Research and Development Act											X

[a] Programs and activities under this heading relate directly to specific sources of ground-water contamination.
[b] This category includes activities such as research and development and grants to the states to develop ground-water related programs.

Table 2. Federal Ground-Water Monitoring Provisions and Objectives (after Office of Technology Assessment, 1984)

Statutory authority	Monitoring provisions[a]	Monitoring objectives
Atomic Energy Act	Ground-water monitoring is specified in Federal regulations for low-level radioactive waste disposal sites. The facility license must specify the monitoring requirements for the source. The monitoring program must include: - Pre-operational monitoring program conducted over a 12-month period. Parameters not specified. - Monitoring during construction and operation to provide early warning of releases of radionuclides from the site. Parameters and sampling frequencies not specified. - Post-operational monitoring program to provide early warning of releases of radionuclides from the site. Parameters and sampling frequencies not specified. System design is based on operating history, closure, and stabilization of the site.	To obtain background water quality data and to evaluate whether ground water is being contaminated.
	Ground-water monitoring related to the development of geologic repositories will be conducted. Measurements will include the rate and location of water inflow into subsurface areas and changes in ground-water conditions.	To confirm geotechnical and design parameters and to ensure that the design of the geologic repository accommodates actual field conditions.
	Ground-water monitoring may be conducted by DOE, as necessary, as part of remedial action programs at storage and disposal facilities for radioactive substances.	
Clean Water Act -Sections 201 and 405	Ground-water monitoring requirements are established on a case-by-case basis for the land application of wastewater and sludge from sewage treatment plants.	To evaluate whether ground water is being contaminated.
-Section 208	No explicit requirements are established; however, ground-water monitoring studies are being conducted by SCS under the Rural Clean Water Program to evaluate the impacts of agricultural practices and to design and determine the effectiveness of Best Management Practices.	To characterize a contamination problem and to select and evaluate the effectiveness of corrective measures.
Coastal Zone Management Act	The statute does not authorize development of regulations for sources. Thus, any ground-water monitoring conducted would be the result of requirements established by a State plan (e.g., monitoring with respect to salt-water intrusion) authorized and funded by CZMA.	
Comprehensive Environmental Response, Compensation, and Liability Act	Ground-water monitoring may be conducted by EPA (or a State) as necessary to respond to releases of any hazardous substance, contaminant, or pollutant (as defined by CERCLA).	To characterize a contamination problem (e.g., to assess the impacts of the situation, to identify or verify the source(s), and to select and evaluate the effectiveness of corrective measures).
Federal Insecticide, Fungicide and Rodenticide Act-Section 3	No monitoring requirements established for pesticide users. However, monitoring may be conducted by EPA in instances where certain pesticides are contaminating ground water.[b]	To characterize a contamination problem.
Federal Land Policy and Management Act (and associated mining laws)	Ground-water monitoring is specified in Federal regulations for geothermal recovery operations on Federal lands for a period of at least one year prior to production. Parameters and monitoring frequency are not specified.	To obtain background water-quality data.
	Explicit ground-water monitoring requirements for mineral operations on Federal lands are not established in Federal Regulations. Monitoring may be required (as permit condition) by BLM.	
Hazardous Liquid Pipeline Safety Act	Although the statute authorizes development of regulations for certain pipelines for public safety purposes, the regulatory requirements focus on design and operation and do not provide for ground-water monitoring.	
Hazardous Materials Transportation Act	Although the statute authorizes development of regulations for transportation for public safety purposes, the regulatory requirements focus on design and operation and do not provide for ground-water monitoring.	
National Environmental Policy Act	The statute does not authorize development of regulations for sources.	

(Continued)

Table 2. (Continued)

Statutory authority	Monitoring provisions[a]	Monitoring objectives
Reclamation Act	No explicit requirements established; however, monitoring may be conducted, as necessary, as part of water supply development projects.	
Resource Conservation and Recovery Act -Subtitle C	Ground-water monitoring is specified in Federal regulations for all hazardous waste land disposal facilities (e.g., landfills, surface impoundments, waste piles, and land treatment units).	
	Facilities in existence on the effective date of statutory or regulatory amendments under the act that would make the facility subject to the requirements to have a RCRA permit must meet *Interim Status* monitoring requirements until a final permit is issued. These requirements specify the installation of at least one upgradient well and three downgradient wells. Samples must be taken quarterly during the first year and analyzed for the National Drinking Water Regulations, water quality parameters (chloride, iron, manganese, phenols, sodium and sulfate), and indicator parameters (pH, specific conductance, TOC and TOX). In subsequent years, each well is sampled and analyzed annually for the six background water-quality parameters and semi-annually for the four indicator parameters.	To obtain background water-quality data and evaluate whether ground water is being contaminated.
	If contaminant leakage has been detected during detection monitoring, the owner or operator of an interim status facility must undertake assessment monitoring. The owner or operator must determine the vertical and horizontal concentration profiles of all the hazardous waste constituents in the plume(s) escaping from waste management units.	
	Ground-water monitoring requirements can be waived by an owner/operator if a written determination indicating that there is low potential for waste migration via the uppermost aquifer to water supply wells or surface water is made and certified by a qualified geologist or engineer. Ground-water monitoring requirements for a surface impoundment may be waived if (1) it is used to neutralize wastes which are hazardous solely because they exhibit the corrosivity characteristic under Section 261.22 or are listed in Subpart D of Part 261 and (2) contains no other hazardous waste. The owner or operator must demonstrate that there is no potential for migration of the hazardous wastes from the impoundment. The demonstration must be in writing and must be certified by a qualified professional.	
	The monitoring requirements for a *fully permitted* facility are comprised of a three-part program:	To obtain background water-quality data or evaluate whether ground water is being contaminated (detection monitoring), to determine whether groundwater quality standards are being met (compliance monitoring), and to evaluate the effectiveness of corrective action measures.
	-*Detection Monitoring* - Implemented when a permit is issued and there is no indication of leakage from a facility. Parameters are specified in the permit. Samples must be taken and analyzed at least semi-annually for active life of regulated unit and the post-closure care period. If there is a statistically significant increase in parameters specified in permit, owner or operator must notify Regional Administrator and sample ground water in all monitoring wells for Appendix IX constituents.	
	-*Compliance Monitoring* - Implemented when ground-water contamination is detected. Monitoring is conducted to determine whether	

(Continued)

Table 2. (Continued)

Statutory authority	Monitoring provisions*	Monitoring objectives
Resource Conservation and Recovery Act (cont.) -Subtitle C (cont.)	or not regulated units are in compliance with the ground-water protection standard specified in facility permit. Samples must be taken and analyzed at least quarterly for parameters specified in the permit. Samples must also be analyzed for a specific list of constituents (Appendix IX to Part 264). -*Corrective Action Monitoring* - Implemented if compliance monitoring indicates that specified concentration levels for specified parameters are being exceeded and corrective measures are required. Monitoring must continue until specified concentration levels are met. Parameters and monitoring frequency not specified. -Exemptions are provided from these regulations for owner or operator exempted under Section 264.1, or if Regional Administrator finds unit is engineered structure; does not receive or contain liquid waste or waste containing free liquids; is designed and operated to exclude liquids precipitation, and other run-on and run-off; has both inner and outer containment layers; has a leak detection system built into each containment layer; owner or operator will provide continuing operation and maintenance of leak detection systems; and to a reasonable degree of certainty will not allow hazardous constituents to migrate beyond the outer containment layer prior to end of post-closure care period.	
-Subtitle D	The 1984 Hazardous and Solid Waste Amendments require EPA to revise criteria for solid waste management facilities that may receive household hazardous waste or small quantity generator hazardous waste. At a minimum, the revisions must require ground-water monitoring, establish location criteria and provide for corrective action. On August 30, 1988, EPA published proposed rules requiring ground-water monitoring at all new and existing municipal solid waste landfills.	
-Subtitle I	Ground-water monitoring is one of the release detection options available for owners and operators of petroleum underground storage tanks. It is also an option at existing hazardous substance underground storage tanks until December 22, 1998. At the end of this period, owners and operators must upgrade or replace this release detection method with secondary containment and interstitial monitoring unless a variance is obtained.	
Safe Drinking Water Act -Part C-Underground Injection Control Program	Ground-water monitoring requirements may be specified in a facility permit for injection wells used for in-situ or solution mining of minerals (Class III wells) where injection is into a formation containing less than 10,000 mg/l TDS. Parameters and monitoring frequency not specified except in areas subject to subsidence or collapse where monitoring is required on a quarterly basis. Ground-water monitoring may also be specified in a permit for wells which inject beneath the deepest underground source of drinking water (Class I wells). Parameters and monitoring frequency not specified in Federal regulations.	To evaluate whether ground water is being contaminated.

(Continued)

Table 2. (Continued)

Statutory authority	Monitoring provisions[a]	Monitoring objectives
Surface Mining Control and Reclamation Act	Ground-water monitoring is specified in Federal regulations for surface and underground coal mining operations to determine the impacts on the hydrologic balance of the mining and adjacent areas. A ground-water monitoring plan must be developed for each mining operation (including reclamation). At a minimum, parameters must include total dissolved solids or specific conductance, pH, total iron, and total manganese. Samples must be taken and analyzed on a quarterly basis. *Monitoring of a particular water-bearing stratum may be waived by* the regulatory authority if it can be demonstrated that it is not a stratum which serves as an aquifer that significantly ensures the hydrologic balance of the cumulative impact area.	To obtain background water-quality data and evaluate whether ground water is being contaminated.
Toxic Substance Control Act -Section 6	Ground-water monitoring specified in Federal regulations requires monitoring prior to commencement of disposal operations for PCBs. Only three wells are required if underlying earth materials are homogenous, impermeable and uniformly sloping in one direction. Parameters include (at a minimum) PCBs, pH, specific conductance, and chlorinated organics. Monitoring frequency not specified. No requirements are established for active life or after closure.	To obtain background water-quality data.

If proper monitoring well design and construction techniques are not employed during monitoring well installation, the data collected from the well may not be reliable. For example, Sosebee et al. (1983) determined that the solvent used to weld lengths of polyvinyl chloride (PVC) casing together can leach significant amounts of tetrahydrofuran, methylethyl ketone, methylbutyl ketone, and other synthetic organic chemicals into water that comes in contact with the solvent-welded casing joint. This could result in false determinations of the presence of certain chemical constituents in water samples taken from PVC wells in which the joints were solvent welded.

Monitoring well installation procedures can also have a significant impact on the integrity of ground-water samples. For example, Brobst and Buszka (1986) found that organic drilling fluids and bentonite drilling muds used in mud rotary drilling can have an effect on the chemical oxygen demand of ground water adjacent to the wellbore in a rotary-drilled well. This, in turn, can affect the quality of a water sample taken from such a well, resulting in the acquisition of non-representative ground-water samples.

Vertical seepage of leachate along well casing can also produce non-representative samples. Monitoring wells are frequently sealed with neat cement grout, bentonite, or a cement-bentonite mixture. The correct choice of a grout and the proper emplacement method to ensure a seal are critical to assure ground-water sample integrity and prevent cross contamination of aquifers. Wehrmann (1983) noted that while a neat cement grout is often recommended, shrinkage and cracking of the cement upon curing can create an improper seal. Kurt and Johnson (1982) have presented the case that the smooth surface of thermoplastic casing provides a potential path for vertical leakage between the casing and the grout material. The implications of the impact of adhesion, including chemical bonding, versus swell pressure have not been documented in the literature. However, it is known that vertical leakage between the casing and the grout material may occur because of swelling and shrinkage during the curing of the grout.

This brief synopsis of potential problems associated with improper monitoring well design and installation illustrates that there are a number of design elements that must be addressed in proper monitoring well construction. This manual attempts to discuss the basic elements that lead to the construction of a viable monitoring well. Where appropriate, potential problems or pitfalls are discussed.

Organization of the Document

This document contains 8 major sections and 3 supporting appendices. A complete list of references can be found immediately following Section 8. Section 1, "Introduction," provides an explanation of the impetus for this "Handbook" and includes a brief discussion of the regulatory framework for ground-water monitoring regulations. Section 2, "Factors Influencing Ground-Water Monitoring Well Design and Installation," discusses the importance of sizing a monitoring well in accordance with the intended purpose of the well. Section 2 also describes the importance of monitoring well location and the influence of hydrogeology, contaminant characteristics and anthropogenic influences on monitoring well design. Section 3, "Monitoring Well Planning Considerations," explains the importance of keeping detailed records during the entire existence of the monitoring well from installation through sampling to abandonment. A discussion of the necessity of decontamination procedures for drilling equipment used during monitoring well installation is also included in this section. Section 4, "Description and Selection of Drilling Methods," includes a brief discussion of drilling and sampling methods used during monitoring well construction and the advantages and disadvantages of each technique. The focus of this section is a set of matrices (included in Appendix B) that indicate favorable drilling techniques for monitoring wells with certain specifications drilled in selected hydrogeologic settings. Section 5, "Design Components of Monitoring Wells," describes the materials and installation techniques for casing, well intakes, and filter packs. A discussion of grout mixtures and emplacement techniques is also presented. Section 6, "Completion of Monitoring Wells," provides a description of well completion techniques and types of well completions designed to maximize collection of representative ground-water samples. Section 7, "Monitoring Well Development," discusses the importance of proper development and describes techniques used in monitoring wells. Section 8, "Monitoring Well Network Management Considerations," discusses the importance of maintenance and proper well abandonment coupled with the necessity for recordkeeping.

Also included within the document are a glossary and three supporting Appendices. The glossary contains pertinent ground-water monitoring terms. Appendix A contains a detailed discussion of installing monitoring wells with a hollow-stem auger. Appendix B includes a set of matrices designed to assist in the selection of drilling technologies. Appendix C is a reproduction of a standard for well abandonment.

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Section 2
Factors Influencing Ground-Water Monitoring Well Design and Installation

Geologic and Hydrogeologic Conditions

The geologic and hydrogeologic conditions at a site affect the occurrence and movement of ground water and contaminant transport in the subsurface. Concomitantly, these two factors significantly influence the design and construction techniques used to install a monitoring well. The following discussion of the geologic and hydrogeologic conditions pertinent to the design and construction of monitoring wells is divided into two parts. The first part addresses regional geologic and hydrogeologic conditions that impact ground-water occurrence, and hence the types of water-bearing materials that are likely to be monitored. Non-exploitable aquifers in some cases, must also be monitored. The second part of this discussion focuses more on site-specific geologic and hydrogeologic conditions that can affect the design of a monitoring well and selection of an appropriate method for drilling and constructing the well.

Hydrogeologic Regions of the United States

Heath (1984) has developed a classification system that 'ivides the United States into ground-water regions based on ground-water occurrence and availability. Because the presence of ground water in the subsurface is closely related to geologic conditions, areas with similar rock composition and structure tend to form similar ground-water regions. The classification system developed by Heath (1984) uses the type and interrelationship of the aquifers in an area as the major division for regional designation. Additional factors including: 1) primary versus secondary porosity, 2) mineral composition of the aquifer, 3) hydraulic characteristics of the aquifer, and 4) the effects of recharge and/or discharge areas were used to further define each region. Figure 1 illustrates the division of the United States into 15 ground-water regions. For the purposes of this discussion, however, Puerto Rico and the Virgin Islands will be excluded. Because the primary focus of this discussion is limited to the hydrogeologic conditions pertinent to monitoring well construction, the reader is referred to Heath (1984) for additional information on each ground-water region.

Western Mountain Ranges —

The Western Mountain Ranges are comprised of tall, massive mountains separated by narrow, steep-sided valleys. In many areas, the mountains have been subjected to alpine glaciation. Major lowland areas occur between the mountain ranges in the southern part of this region. With geologic origins related to major orogenic and tectonic events, most of the mountain ranges are comprised of metamorphic and igneous rocks flanked by consolidated sedimentary rocks of Paleozoic Cenozoic age. Other mountain ranges such as the Cascades and the San Juan mountains are composed primarily of basaltic lava.

Bare bedrock exposures or a thin layer of weathered material cover the slopes and summits of the mountains. The weathered layer tends to thicken toward the base of the mountains and in the alluvial valleys. Figures 2a and 2b illustrate the location and main geologic and hydrogeologic features of this region. Despite high precipitation rates in the region, ground-water resources are primarily limited to the storage capacity of the fractures in the crystalline rocks that serve as an aquifer for this area. The lowlands between the mountain ranges contain thick deposits of fine to coarse-grained alluvium eroded from the adjacent mountains. These deposits serve as aquifers that are capable of supplying moderate to large yields to wells. The alluvial aquifers are often in direct hydraulic connection with the underlying bedrock.

Alluvial Basins —

The Alluvial Basins region is comprised of thick alluvial deposits in structural lows alternating with igneous and metamorphic mountain ranges. This region covers two distinctive areas: 1) the Basin and Range area of the southwest and 2) the Puget Sound/Willamette Valley Area of the Pacific Northwest (Figure 3a).

The Basin and Range area consists of basins filled with thick deposits of unconsolidated alluvial material eroded from the adjacent mountains and deposited as coalescing alluvial fans. The alluvial materials in the fans are typically coarsest near the mountains and become progressively finer toward the center of the basin. These basins typically form closed-basin systems where no surface or subsurface flow leaves the region. However, water may move through the permeable deposits and actually move between basins in a complex hydrogeologic relationship as illustrated in Figure 3b. Most ground water in this region is obtained from the permeable sand and gravel deposits that are interbedded with finer-grained layers of saturated silts and clays.

The alluvial deposits of the Puget Sound were deposited by sediment-laden meltwater from successive glaciations. Thick layers of permeable sands and gravels that are interbedded with discontinuous clay layers provide the majority of the water resources for this area. The Willamette Valley consists of interbedded sands, silts and clays deposited by the Willamette River and related streams. High precipitation rates in the region provide the major source of recharge to these aquifers.

The mountains bordering these alluvial basins consist of igneous and metamorphic rocks ranging from Precambrian to Tertiary in age. The limited water resources in the mountains are derived from water stored in fractures in the bedrock.

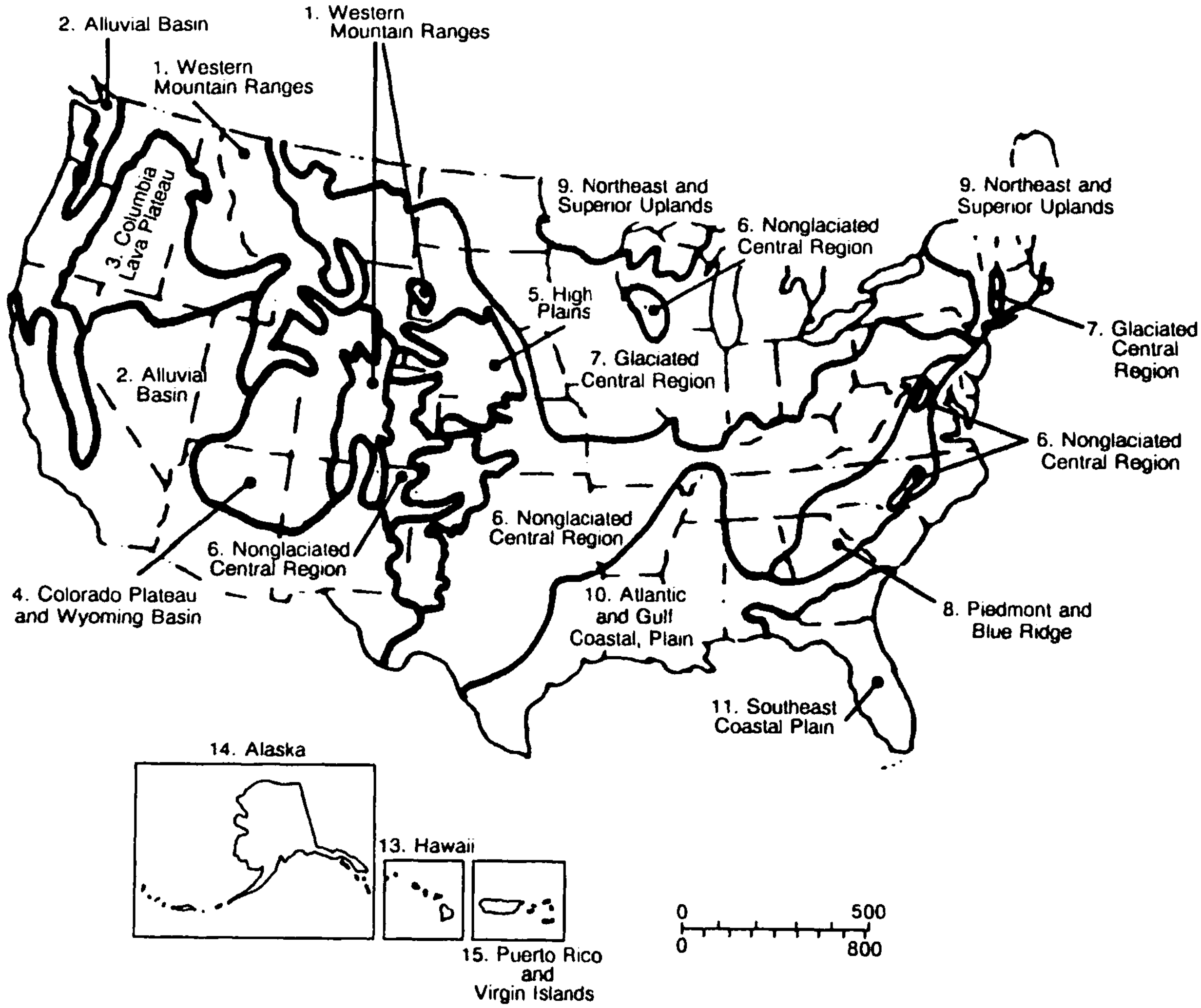
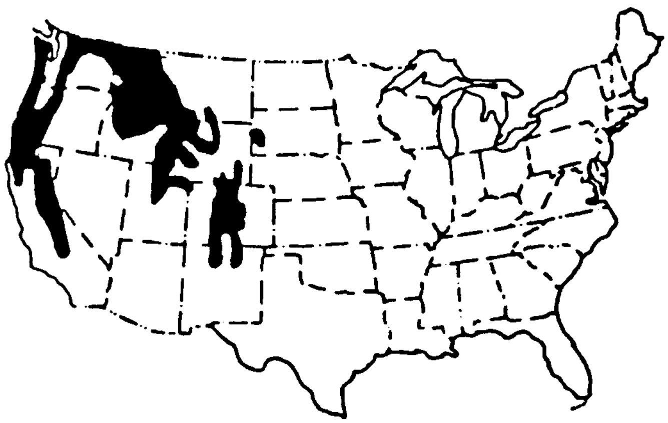


Figure 1. Ground-water regions of the United States (Heath, 1984).



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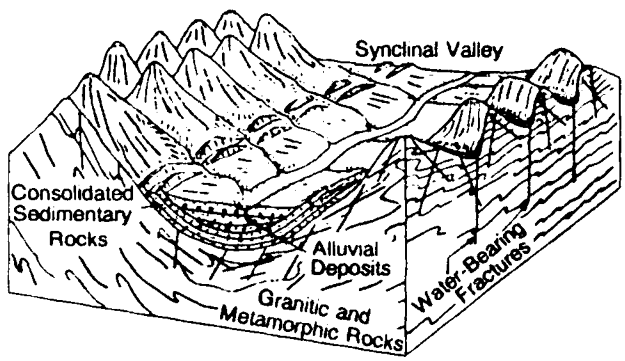
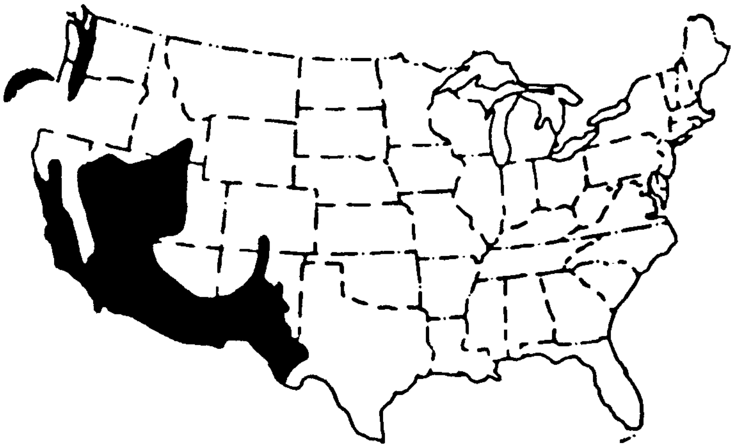


(b)

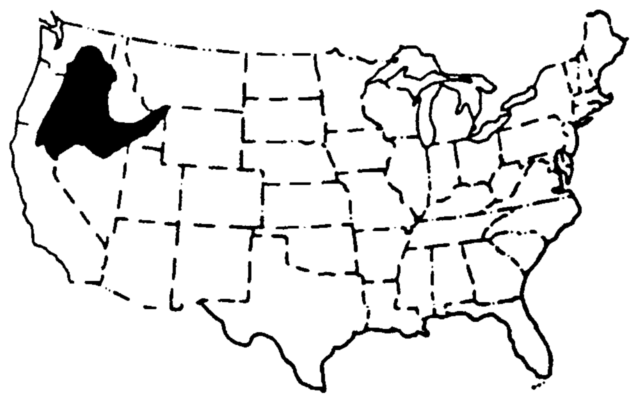
Figure 2a. Location of the Western Mountain Ranges region (Heath, 1984).

Figure 2b. Topographic and geologic features in the southern Rocky Mountains part of the Western Mountain Ranges region (Heath, 1984).



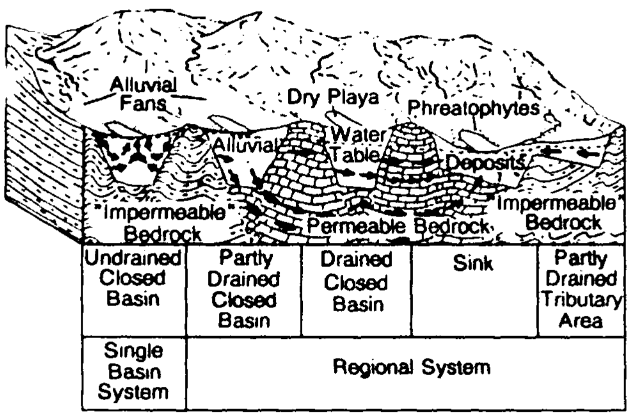
(a)

Figure 3a. Location of the Alluvial Basins region (Heath, 1984).



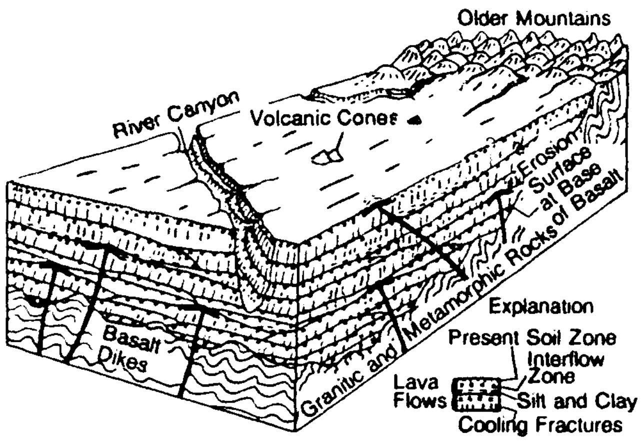
(a)

Figure 4a. Location of the Columbia Lava Plateau region (Heath, 1984).



(b)

Figure 3b. Common ground-water flow systems in the Alluvial Basins region (Heath, 1984).



(b)

Figure 4b. Topographic and geologic features of the Columbia Lava Plateau region (Heath, 1984).

Columbia Lava Plateau —

The Columbia Lava Plateau consists of a sequence of lava flows ranging in total thickness from less than 150 feet adjacent to mountain ranges to over 3,000 feet in south-central Washington and northern Idaho (Figure 4a). The lava is composed of basalt that erupted from extensive fissures and produced large sheet-like flows. The lava beds comprise the principal water-bearing unit in the region.

Ground water in basalt flows through the permeable zones that occur at the contacts between the lava flow layers (Figure 4b). The permeable zones result from the cooling of the crust on the molten lava as it continues to flow thus producing a zone of fragments and gas bubbles near the top of the lava sheet. Cooling of the lava sheet itself also produces vertical fracturing within the basalt. These interflow zones, created by the cooling crust, form a complex series of relatively horizontal aquifers separated by denser layers of basalt that are often hydraulically interconnected by the intersecting fractures and faults within the lava sheets.

The region can be divided into two separate hydrogeologic flow regimes. The Columbia River Group, in the western part of this region, consists of relatively thick basalt flows that have been offset by normal faults. Primary water movement is through shallow interflow zones. The aquifers are typically poorly hydraulically interconnected because the flow is controlled by the faults which form barrier-controlled reservoirs.

The remainder of the region, occupied by the Snake River Plain, consists of a series of thin lava flows with well-developed interflow zones and extensive fracturing. These interflow zones exhibit high hydraulic conductivities and are hydraulically interconnected by cooling fractures. The large differences in hydraulic conductivity between the interflow zones and the denser basalt often result in significant differences in hydraulic head between aquifers. Consequently, there is the potential for the movement of water between aquifers through uncased or improperly cased wells.

Recharge to the aquifer is from precipitation and infiltration from streams that flow onto the plateau from adjacent mountains. Irrigation of crops in this region provides additional recharge to the aquifer through the interflow zones when the source of water is not from the aquifer.

Colorado Plateau and Wyoming Basin —

The Colorado Plateau and Wyoming Basin region is characterized by a broad structural plateau underlain by horizontal to gently dipping beds of consolidated sedimentary rock. In some areas, the structure of the plateau has been modified by faulting and folding that resulted in basin and dome features. The region contains small, isolated mountain ranges as well as extinct volcanoes and lava fields (Figures 5a and 5b).

The sedimentary rocks in this region consist of Paleozoic- to Cenozoic-age sandstones, limestones and shales. Evaporitic rocks such as gypsum and halite also occur in some areas. The sandstones serve as the principal source of ground water. Water within the sandstone is contained within pore spaces and in fractures and bedding planes. Minor deposits of unconsolidated alluvium occur in major river valleys and contribute small to moderate yields of ground water.

Recharge to the aquifers is from precipitation and from infiltration from streams that cross the outcrop areas. The gentle dip of the beds causes unconfined conditions in outcrop areas and confined conditions downdip. Aquifers in the region frequently contain mineralized water at depth. Aquifers typically discharge to springs and seeps along canyon walls.

High Plains —

The High Plains region represents a remnant of an alluvial plain deposited by streams and rivers that flowed eastward from the Rocky Mountains during the Tertiary period. Extensive erosion has subsequently removed a large portion of the plain, including most areas adjacent to the mountains.

The High Plains region is underlain primarily by the Ogallala formation, a thick deposit of semi-consolidated alluvial materials consisting of poorly-sorted sands, gravels, silts and clays (Figures 6a and 6b). The Ogallala formation is the major aquifer and is overlain locally by younger alluvial material that is often saturated and forms a part of the aquifer. In places where the Ogallala is absent, these younger alluvial deposits, that are comprised of unconsolidated sand, gravel, silt and clay, are used as the major aquifer. Extensive areas of surficial sand dunes are also present. In some areas, older underlying consolidated deposits that include the fine-grained sandstones of the Arikaree Group and Brule formation are

(a)

Figure 5a. Location of the Colorado Plateau and Wyoming Basin region (Heath, 1984).

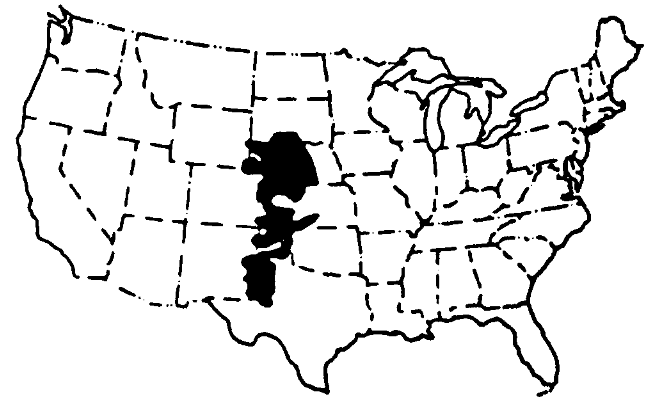


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Figure 6a. Location of the High Plains region (Heath, 1984).

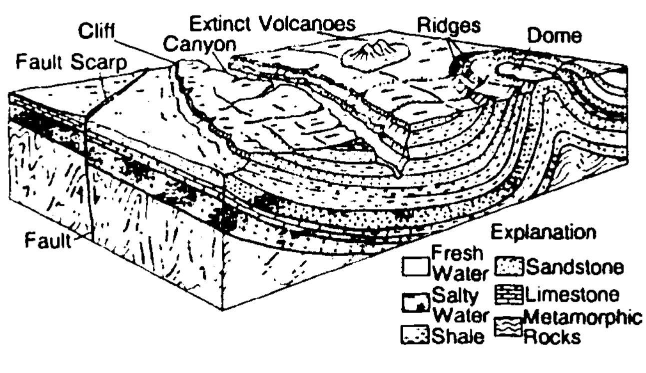

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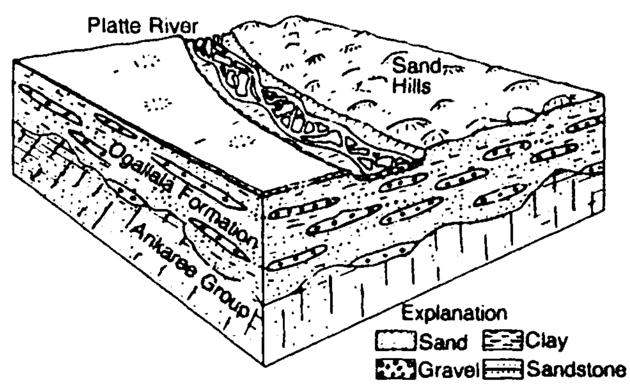
Figure 5b. Topographic and geologic features of the Colorado Plateau and Wyoming Basin region (Heath, 1984).



(b)

Figure 6b. Topographic and geologic features of the High Plains region (Heath, 1984).

hydraulically connected to the Ogallala. Where these deposits are absent, the Ogallala is underlain by other sedimentary rocks that often contain unusable, highly mineralized water.

Recharge to the aquifer from precipitation varies across the area. The presence of caliche, a low permeability calcium carbonate layer at or near the land surface, limits the amount of precipitation that infiltrates to the aquifer, thereby increasing the amount of water lost to evapotranspiration. In the sand dunes area, however, the permeability of the surface materials allows increased recharge to the aquifer.

Extensive development of the aquifer for agricultural irrigation has led to long-term declines in water levels. Where ground-water withdrawal rates have exceeded available recharge to the aquifer, ground-water mining has occurred. The depletion of water from storage in the High Plains region has resulted in a decrease in the saturated thickness of the aquifer in areas of intensive irrigation.

Nonglaciated Central Region —

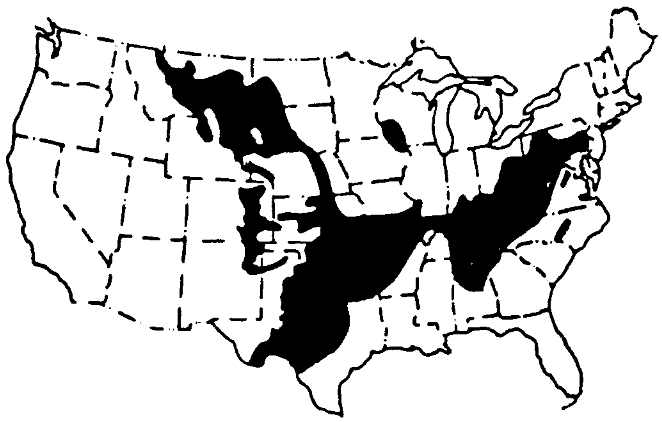
The Nonglaciated Central region covers a geologically complex area extending from the Appalachian Mountains to the Rocky Mountains. Most of the region is underlain by consolidated sedimentary rocks, including sandstones, shales, carbonates and conglomerates that range from Paleozoic to Tertiary in age (Figures 7a, 7b and 7c). These rocks are typically horizontal to gently dipping with the exception of a few areas, notably the Valley and Ridge section; the Wichita and Arbuckle mountains in Oklahoma; the Ouachita Mountains in Oklahoma and Arkansas; and the Triassic basins in Virginia and North Carolina. The Triassic basins contain interbedded shales, sandstones and conglomerates that have been faulted and invaded by igneous rocks.

Chemical and mechanical weathering of the bedrock has formed a layer of regolith that varies in thickness and composition depending on the composition and structure of the underlying parent rock and the effects of climate and topography. The sandstones and limestones constitute the major aquifers in the area. Water occurs primarily in bedding planes and fractures in the bedrock. Many of the limestones contain solution channels that increase the permeability. Limestones in this region often form extensive cave systems that directly affect patterns of ground-water flow.

Recharge in the region occurs primarily from precipitation in outcrop areas and varies widely. Small to moderate well yields are common; higher yields may be available in karstic areas. Well yields often depend on the size and number of fractures intersected by the well, the recharge to the area and the storage capacity and permeability of the bedrock and/or regolith. In many parts of this region, mineralized water occurs at depths greater than 300 feet.

Glaciated Central Region —

The geology of the Glaciated Central region is characterized by relatively horizontal sedimentary rocks of Paleozoic to Tertiary age consisting of sandstones, shales and carbonates. The bedrock is overlain by varying thicknesses of poorly-sorted glacial till that is interbedded with: 1) well-sorted sands and gravels deposited from meltwater streams, 2) clays and silts



(a)

Figure 7a. Location of the Nonglaciated Central region (Heath, 1984).

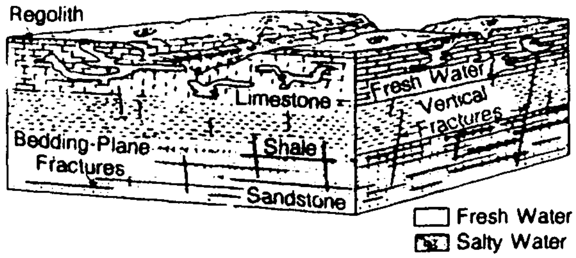


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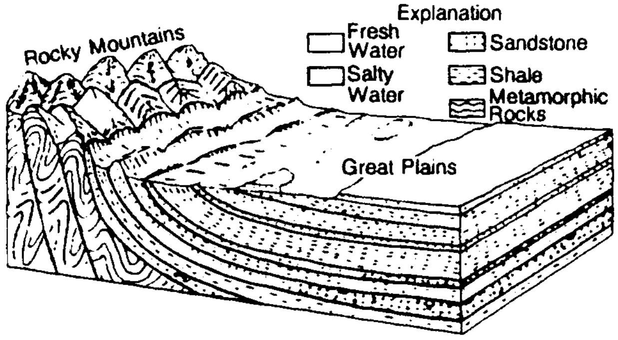
Figure 7b. Topographic and geologic features of the Nonglaciated Central region (Heath, 1984).



(c)

Figure 7c. Topographic and geologic features along the western boundary of the Nonglaciated Central region (Heath, 1984).

from glacial lake beds and 3) wind-blown silt or loess deposits (Figures 8a and 8b).

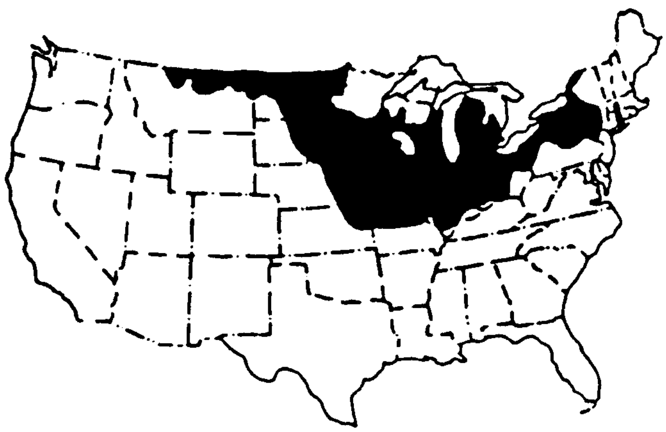
In the eastern part of the region, the glacial deposits are typically thin on the uplands and thicken locally in valleys. Toward the central and western parts of the region, glacial deposits are thicker and often mask the location of preglacial river valleys. These thick deposits in the preglacial river valleys often contain permeable sands and gravels that form major aquifers with significant well yields. Overlying till deposits often act as confining layers for the underlying sand and gravel aquifers.

The underlying bedrock in this region also commonly serves as an aquifer. Water occurs primarily along bedding planes and in fractures. Frequently the glacial deposits and the bedrock are hydraulically interconnected. The glacial deposits often provide recharge to the bedrock aquifers and serve as a source of water for shallow wells. Movement of poor-quality water from the bedrock into the glacial deposits may cause local ground-water quality problems. Recharge to the glacial deposits is provided by precipitation and by infiltration from streams. Recharge rates primarily vary with precipitation rates, evapotranspiration rates, permeability of the glacial materials and topography.

Ground-water supplies are abundant in this area; well yields are moderate to high. Smaller yields are expected in areas where the glacial deposits are fine-grained or where the underlying bedrock has an insufficient amount of fractures or solutioning. Because of the widespread occurrence of carbonate rocks, ground water in these areas frequently exhibits high hardness.

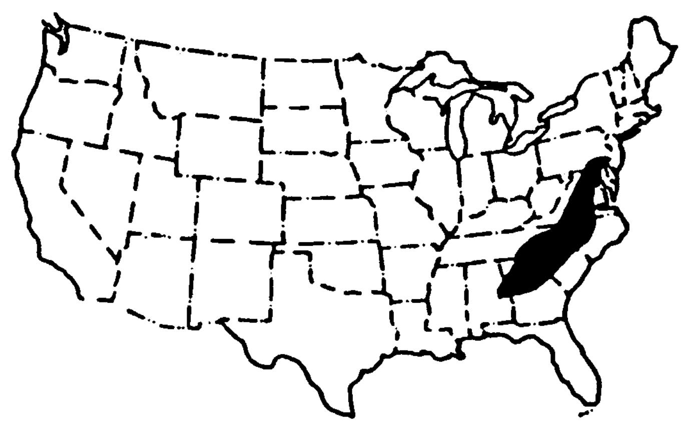
Piedmont and Blue Ridge —

The Piedmont lies between the coastal plain and the Appalachian Mountains. The region is characterized by a series of low, rounded hills that gradually increase in height toward the west and culminate in the parallel ranges of the Appalachian Mountains in the north and the Blue Ridge Mountains in the south. The bedrock of the region consists of Precambrian to Mesozoic-age igneous, metamorphosed-igneous and sedimentary rocks (Figures 9a and 9b).



(a)

Figure 8a. Location of the Glaciated Central region (Heath, 1984).



(a)

Figure 9a. Location of the Piedmont and Blue Ridge region (Heath, 1984).

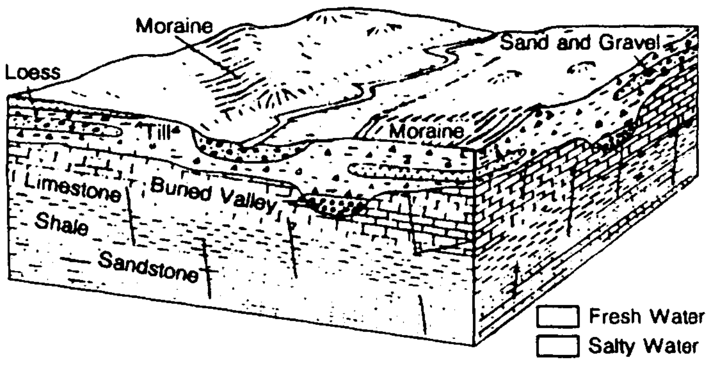


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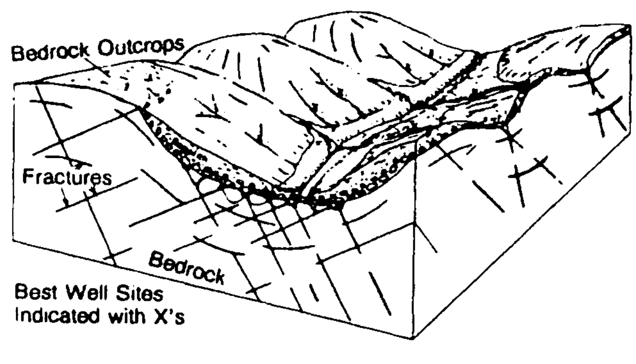
Figure 8b. Topographic and geologic features of the Glaciated Central region (Heath, 1984).



(b)

Figure 9b. Topographic and geologic features of the Piedmont and Blue Ridge region (Heath, 1984).

Active chemical and physical weathering of the bedrock has formed a clay-rich, unconsolidated deposit that overlies bedrock. This deposit, called saprolite or regolith is typically hinner on ridges and thickens on slopes and in valleys. Larger streams in many valleys have deposited significant thicknesses of well-sorted alluvial materials that often overlie the saprolite.

The regolith serves two purposes in the ground-water system: 1) the regolith yields small to moderate quantities of water to shallow wells and 2) the regolith serves as a storage reservoir to slowly recharge the bedrock aquifer. The storage capacity in the bedrock is limited because the ground water occurs along fractures and in joints. Water-supply wells are often completed in both the regolith and in the bedrock.

Well yields in this region are extremely variable; bedrock wells that intersect fractures and/or have sufficient recharge from the overlying regolith are the most productive. A higher density of fractures typically occurs along valleys and in draws bordering ridges.

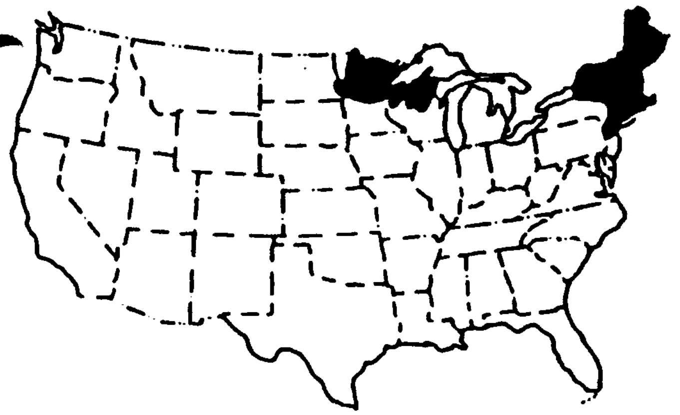
Northeast and Superior Uplands —

The Northeast and Superior Uplands cover two geographic areas: 1) the Northeast includes the Adirondack Mountains and most of New England, and 2) the Superior Uplands include most of northern Minnesota and Wisconsin. Both areas are underlain by Precambrian to Paleozoic-age igneous and metamorphic rocks that have been intruded by younger igneous rocks and have been extensively folded and faulted (Figures 10a and 10b).

The bedrock is overlain by unconsolidated glacial deposits that vary in thickness. These glacial deposits include poorly-sorted glacial tills, glacial lake clays, and well-sorted sands and gravels laid down by meltwater streams. The glacial sands and gravels serve as important aquifers and are capable of producing moderate to large yields. Ground water in the bedrock is typically found in fractures or joints and the rock has a low storage capacity. The glacial deposits provide recharge by slow seepage to the underlying bedrock. Wells are often completed in both bedrock and the glacial deposits to provide maximum yields. Recharge to the glacial deposits occurs primarily from precipitation.

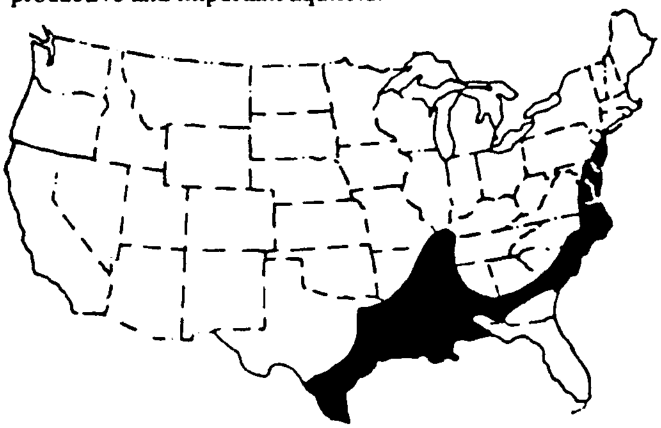
Atlantic and Gulf Coastal Plain —

The Atlantic and Gulf Coastal Plain region extends southward from Cape Cod to the Rio Grande River in Texas. The region is underlain by Jurassic to Recent-age semi-consolidated to unconsolidated deposits of sand, silt and clay laid down by streams draining the adjacent upland areas. These deposits are very thin toward the inner edge of the region and thicken southward and eastward. The thickest deposits occur in a down-warped zone termed the Mississippi Embayment. All deposits either dip toward the coast or toward the axis of the embayment; therefore, the older formations outcrop along the inner part of the region and the youngest outcrop along the gulf coastal area. Coarser-grained material is more abundant updip, and clay and silt layers tend to thicken downdip (Figures 11a and 11b). Limestone and shell beds also occur in some areas and serve as productive and important aquifers.



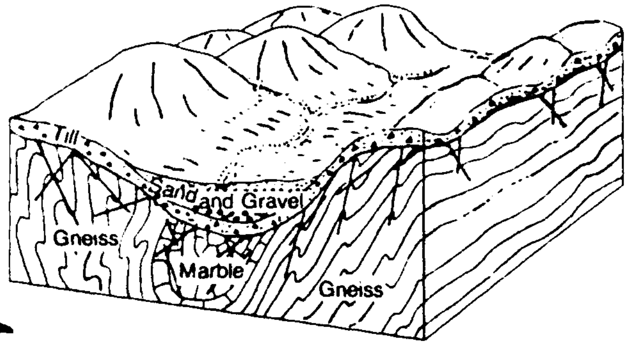
(a)

Figure 10a. Location of the Northeast and Superior Uplands region (Heath, 1984).



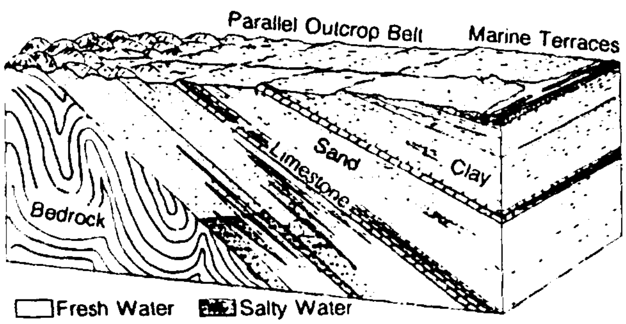
(a)

Figure 11a. Location of the Atlantic and Gulf Coastal Plain region (Heath, 1984).



(b)

Figure 10b. Topographic and geologic features of the Northeast and Superior Uplands region (Heath, 1984).



(b)

Figure 11b. Topographic and geologic features of the Gulf Coastal Plain (Heath, 1984).

Recharge to the aquifer occurs in outcrop areas from precipitation and from infiltration along streams and rivers. In some areas an increase downdip in the percentage of clay in the deposits limits recharge and affects ground-water flow paths. Ground-water withdrawals in these areas sometimes exceed recharge to the aquifer and result in declining water levels and land subsidence.

Southeast Coastal Plain —

The Southeast Coastal Plain includes all of Florida and the southern parts of Alabama and Georgia. The surficial deposits in this area are comprised of unconsolidated Pleistocene-age sand, gravel, silt and shell beds. The semi-consolidated limestone beds of the Biscayne aquifer outcrop in southern Florida. Throughout much of the region, surficial deposits are underlain by the Hawthorn formation, a Miocene-age clay and silt layer. The Hawthorn formation often serves as a confining layer. The Hawthorn formation overlies a thick sequence of semi-consolidated to consolidated limestones and dolomites known as the Floridan aquifer (Figures 12a and 12b).

The Floridan aquifer is one of the most productive aquifers in the United States and is the principal ground-water resource for the entire region. In the northern part of the region, the Floridan is unconfined. Most recharge to the aquifer occurs from direct infiltration of precipitation in this area. In central and southern Florida, the aquifer is semi-confined by the Hawthorn formation and recharge from the surface is limited. Natural discharge from the Floridan occurs from springs and streams and from seepage through confining beds. Many springs with high discharge rates can be found where the Floridan outcrops.

In southern Florida, water in the Floridan is typically saline. In this area, water supplies are developed in the shallower Biscayne aquifer. The Biscayne is unconfined and is recharged directly by precipitation and by infiltration from streams and impoundments.

The surficial sands and gravels also serve as aquifers in many parts of the region, particularly where the Floridan is saline. These aquifers supply small to moderate yields to wells and are recharged by infiltration of precipitation.

Alluvial Valleys —

The Alluvial Valleys region encompasses the thick sand and gravel deposits laid down by streams and rivers. Figure 13a illustrates the extent and location of these major alluvial valleys. Alluvial valleys typically contain extensive deposits of sands and gravels that are often interbedded with overbank deposits of silts and clays. The origin of many of the alluvial aquifers is related to Pleistocene continental and alpine glaciation. Sediment-laden meltwater from the glaciers deposited extensive sands and gravels in many stream valleys. These permeable sands and gravels are capable of yielding moderate to large water supplies to wells. These aquifers are typically confined to the boundaries of the flood plain and to adjacent terraces (Figure 13b).

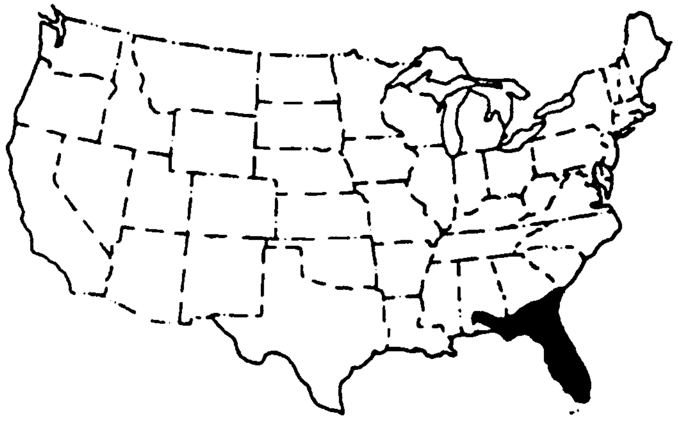
In many of the alluvial valleys, ground-water systems and surface water systems are hydraulically interconnected. Recharge to the aquifer occurs from streams and from precipitation. Withdrawals of ground water near a stream may cause a reversal of hydraulic gradients; ground water previously flowing from the aquifer and discharging to the stream may now receive recharge from the stream by induced infiltration.

Hawaiian Islands —

The Hawaiian Islands were formed by volcanic eruptions of lava. These shield volcanoes rise from the ocean floor and form the eight major Hawaiian islands. Erosion of the volcanoes has carved distinctive valleys and has created an adjacent narrow coastal plain.

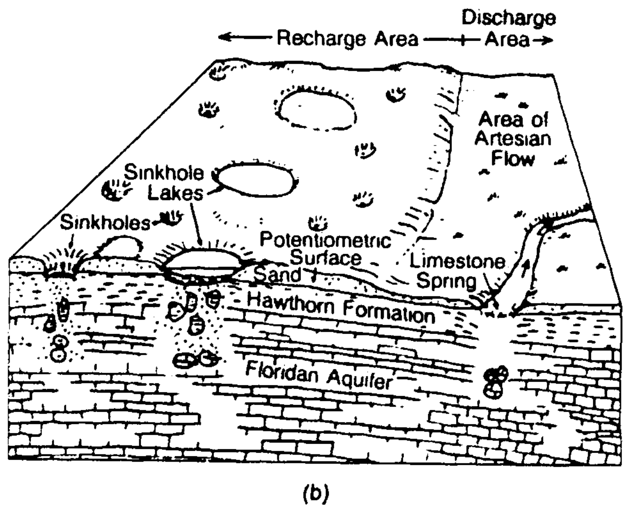
The islands are formed from hundreds of separate lava flows composed primarily of basalt. The lavas that were extruded beneath the sea are relatively impermeable. Lavas that were extruded above sea level contain permeable interflow zones, lava tubes and cracks and joints formed while the lava cooled. Lava flows in the valleys are often covered by a thin layer of alluvium eroded from the basalt.

The mode of deposition of the basalt largely controls the occurrence and flow of ground water on the islands. The ground-water system consists of three major parts: 1) dike-impounded water, 2) basal ground water, and 3) perched



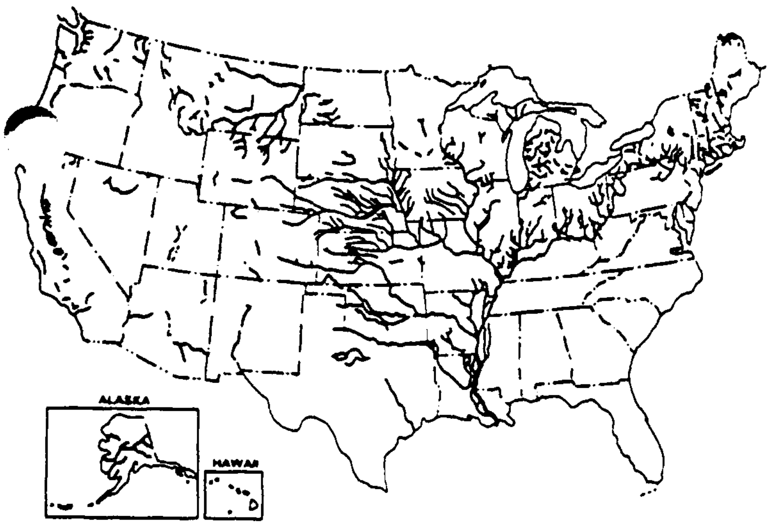
(a)

Figure 12a. Location of the Southeast Coastal Plain Region.



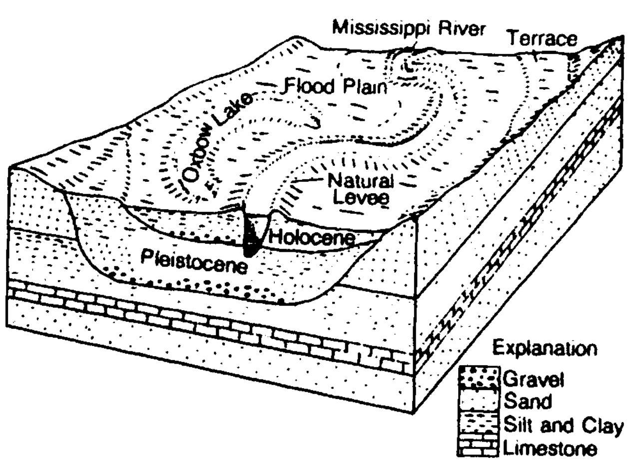
(b)

Figure 12b. Topographic and geologic features of the Southeast Coastal Plain (Heath, 1984).



(a)

Figure 13a. Location of the Alluvial Valleys ground-water region (Heath, 1984).



(b)

Figure 13b. Topographic and geologic features of a section of the alluvial valley of the Mississippi River (Heath, 1984).

(fresh) water (Figure 14). Dike-impounded water is found in the joints developed along the vertical fissures through which the lava erupted. Basal ground water is found in the permeable zones of the horizontal lava flows extending from the eruption centers and is partially hydraulically interconnected to the dike-impounded water. The perched (fresh) water system is found in permeable lava or alluvial deposits above thick impermeable lava flows or basal ground water.

Recharge to these aquifers occurs through the infiltration of precipitation. Because the volcanic soils are highly permeable, approximately thirty percent of the precipitation infiltrates and recharges the aquifer.

The basal ground-water system is the principal source of water to the islands. The basal system occurs as a fresh-water lens floating on the denser sea water. Basal and dike-impounded ground water is often withdrawn from horizontal tunnels and vertical and inclined wells constructed into the lava flows.

Alaska —

Alaska can be divided into four physiographic divisions from south to north: 1) the Pacific Mountain System, 2) the Intermontane Plateaus, 3) the Rocky Mountain System and 4) the Arctic Coastal Plain. The mountain ranges are comprised of Precambrian to Mesozoic-age igneous and metamorphic rocks. These are overlain by younger sedimentary and volcanic rocks. Much of the region is overlain by unconsolidated deposits of gravel, sand, silt, clay and glacial till (Figure 15).

Climate directly affects the hydrology of Alaska. Much of the water at the surface and in the subsurface is frozen throughout much of the year, forming a zone of permafrost or perennially frozen ground. Permafrost occurs throughout the state

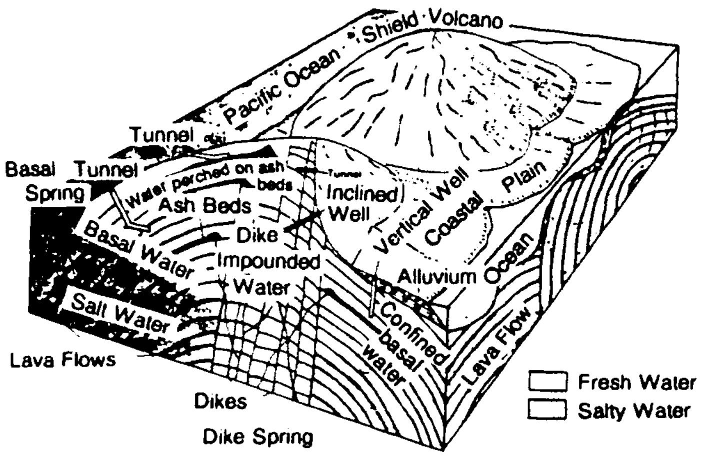


Figure 14. Topographic and geologic features of an Hawaiian Island (Heath, 1984).

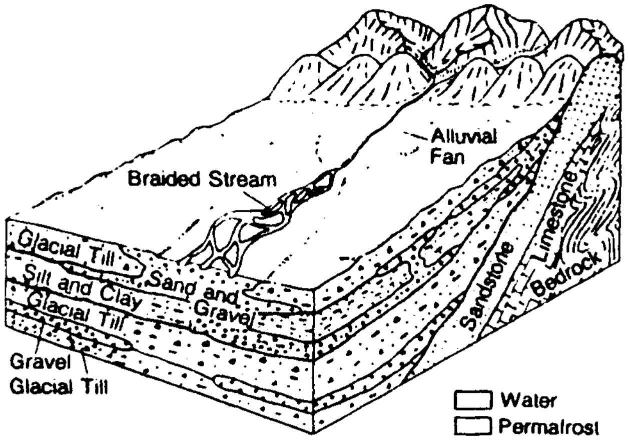


Figure 15. Topographic and geologic features of parts of Alaska (Heath, 1984).

except along the southern and southeastern coasts. The depth of permafrost varies, but is typically deeper in the northern areas and becomes shallower toward the south.

In zones of continuous permafrost, ground water occurs beneath the permafrost and in isolated zones beneath deeper lakes and alluvial channels. In zones of discontinuous permafrost, ground water occurs below the permafrost and in sand and gravel deposits in major alluvial valleys. In the areas where permafrost is absent, ground water occurs both in the bedrock and in the overlying unconsolidated deposits.

Recharge to the aquifers is limited due to permafrost. Even in non-permafrost areas, shallow ground water is usually frozen when spring runoff occurs. Most recharge to the aquifers occurs from stream infiltration as the streams flow across the alluvial deposits when permafrost is absent.

Site-Specific Geologic and Hydrogeologic Conditions

The geologic and hydrogeologic conditions at a specific site influence the selection of an appropriate well design and drilling method. Prior to the installation of monitoring wells, exploratory borings and related subsurface tests must usually be made to define the geology beneath the site and to assess ground-water flow paths and velocity. Formation samples and other data collected from this work are needed to define the hydraulic characteristics of the underlying materials. The logs of these borings are used to correlate stratigraphic units across the site. An understanding of the stratigraphy, including the horizontal continuity and vertical thickness of formations beneath the site, is necessary to identify zones of highly permeable materials or features such as bedding planes, fractures or solution channels. These zones will affect the direction of ground-water flow and/or contaminant transport beneath the site. Because the occurrence and movement of ground water in the subsurface are closely related to the geology, the geologic conditions at the site influence the location, design and methods used to install monitoring wells.

The required depth of a monitoring well is determined by the depth to one or more water-bearing formations that need to be monitored. Where two or more saturated zones occur beneath a site and the intent of the monitoring program is to monitor water quality in the lower zone, the monitoring well may require surface casing to "seal-off" the upper water-bearing formation prior to drilling deeper.

The formations at the site, whether consolidated or unconsolidated, also influence the type of well completion. In unconsolidated deposits, screened intakes are typically designed. The well may have either a naturally-developed or artificially-emplaced filter pack, depending on the grain-size distribution of the water-bearing materials. Artificial filter packs and screened intakes are also often required in poorly-consolidated formations to minimize potential caving of the borehole and/or to reduce turbidity in water samples collected from the completed well. In some consolidated formations, the well may be completed as a cased borehole with no screen intake or filter pack. Where conduit-born fines are a problem in consolidated formations, an artificial filter pack and a screen intake may be required.

Drilling methods must be chosen based at least in part on geologic considerations. Hard, consolidated formations restrict or eliminate certain drilling methods. For example, in karstic formations, cavernous openings create significant problems in maintaining circulation and in protecting drilling equipment. Unconsolidated deposits can also present severe limitations for various drilling methods. Some drilling techniques cannot be used where large boulders are present. Conversely, cohesive geologic deposits and the resultant stability of the borehole may expand drilling options. Variations in equipment, drilling techniques and installation procedures may be necessary to overcome specific limitations when using particular drilling methods.

Consideration of the hydrogeology at the site is also important when selecting a drilling method. The depth to which the well must be drilled to monitor a selected water-bearing zone may exceed the practical depths of a particular drilling technique. In addition, certain saturated geologic materials, under high hydrostatic pressures, may either: 1) impose increased frictional resistance (i.e. expanding clays) which limits the practical depths reached by some drilling methods or 2) create unstable borehole conditions (i.e. heaving sands) that may preclude the use of some drilling methods for installation of the monitoring well.

For a complete discussion of well drilling methods and a matrix for selecting a drilling method based on the general hydrogeologic conditions and well design requirements, the reader is referred to Section 4, "Description and Selection of Drilling Methods."

Facility Characteristics

Frequently the purpose of a monitoring program is to evaluate whether or not ground water is being contaminated from a waste disposal practice or a commercial operation associated with the handling and storage of hazardous materials. In these instances, the design and construction of the monitoring wells must take into account the type of facility being monitored and the fate and transport in the subsurface of the waste materials or commercial products.

Recognition of the type of facility being monitored is necessary to determine whether the facility is regulated under existing federal and/or stage statutes and administrative rules (see Section 1). Some regulated facilities must comply with specific ground-water monitoring requirements, and program-specific guidance documents may describe the design and construction of the monitoring wells. The type of facility or operation may also determine the types of materials and potential contaminants which have been handled onsite, past or present, and whether or not those contaminants were stored or disposed of on or below the ground surface. The design of the facility may also include a system for waste or product containment that impacts potential release of contaminants, both onsite and offsite, and may require separate monitoring.

The physical and chemical characteristics of the contaminants, including volatility, solubility in water and specific density, influence the movement of the contaminant in the subsurface. Additional factors that affect contaminant fate and transport include: oxidation, sorption and biodegradation.

Monitoring wells must be located and designed with these environmental factors and contaminant characteristics in mind. Construction materials for the well should be selected based on their ability to withstand attack by contaminants that are anticipated at the site.

The following two-part discussion focuses on facility characteristics that impact the design and construction of monitoring wells. The first part presents the more prominent types of waste disposal facilities or commercial operations for which ground-water monitoring wells are designed. The second part focuses on those physical and chemical characteristics of contaminants that significantly influence the transport of the contaminant in the subsurface.

Type of Facility

Landfills —

A landfill is a facility or waste unit where solid waste is typically disposed of by spreading, compacting and covering the waste. The landfill design, construction and operation details vary depending on the physical conditions at the site and the type and amount of solid waste to be disposed. Wastes are usually emplaced and covered in one of three settings: 1) on and above the natural ground surface where surface topography is flat or gently rolling, 2) in valleys, ravines or other land depressions, or 3) in trenches excavated into the subsurface. The design of the landfill determines the boundaries of the fill area and the lowest elevation at which the solid waste is disposed. The physical dimensions of the landfill are important criteria for locating and designing the depth of monitoring wells used to monitor the quality of ground water in the first water-bearing zone beneath the bottom of the landfill.

The wastes that are disposed of in landfills are generally classified as either hazardous or non-hazardous. Wastes that are characterized as hazardous are regulated in Title 40 of the United States Code of Federal Regulations (CFR) Part 261. The distinction between a landfill receiving hazardous waste versus non-hazardous waste is important from a regulatory standpoint when developing a ground-water monitoring program. Landfills receiving wastes classified as hazardous are subject to minimum federal regulations for the design and operation of the landfill (40 CFR, Parts 264 and 265, Subpart N and Part 268) and for ground-water protection and monitoring (40 CFR, Parts 264 and 265, Subpart F). These regulations are mandated under the Resource Conservation and Recovery Act (RCRA) and subsequent amendments to RCRA. Individual states may be authorized by the United States Environmental Protection Agency to enforce the minimum federal regulations and may adopt separate state regulations more stringent than the federal standards.

Landfills receiving non-hazardous wastes are also regulated under RCRA; however, these facilities are addressed under different federal guidelines or recommendations for the design and operation of sanitary landfills and for ground-water protection measures (40 CFR, Part 241, Subpart B). Properly designed landfills should include a bottom liner of compacted, low permeability soil and/or synthetic liner to minimize the percolation of leachate from the landfill into the subsurface. A leachate collection system should also be installed beneath the landfill to control leachate migration and permit the collection of leachate for final treatment and disposal. Hazardous waste landfills are subject to minimum, federal technological guidelines for "composite double liner systems" (including compacted low permeability soils and two flexible synthetic membranes) that incorporate both primary and secondary leachate collection systems. Many older or abandoned landfills containing both hazardous and/or non-hazardous wastes are unlined and have been unregulated throughout the operational life of the facility.

Ground-water monitoring programs at hazardous waste land disposal facilities are also subject to federal requirements, including performance criteria. The regulations require that a sufficient number of wells be constructed at appropriate locations and depths to provide ground-water samples from the uppermost aquifer. The purpose of ground-water monitoring is to determine the impact of the hazardous waste facility on ground water in the uppermost aquifer. This is done by comparing representative samples of background water quality to samples taken from the downgradient margins of the waste management area. The ground-water monitoring wells must be properly cased, completed with an artificial filter pack, where necessary, and grouted so that representative ground-water samples can be collected (40 CFR, Sections 264.97 and 265.91). Guidance for the design and construction of these monitoring wells is provided in the RCRA Ground Water Monitoring Technical Enforcement Guidance Document (TEGD). Owners and operators should be prepared to provide evidence that ground-water monitoring measures taken at concerned facilities are adequate.

A potential monitoring problem at all landfills, particularly older facilities, is the accurate location of the boundaries of the landfill. If the boundaries of the fill area are unknown, monitoring wells may not be accurately placed to properly define subsurface conditions with respect to the actual location of the disposal site. Accidental drilling into the landfill causes safety and health concerns. All personnel involved in the drilling of monitoring wells at hazardous waste treatment, storage and disposal facilities, or in the direct supervision of such drilling, should have received initial training in working in hazardous environments in accordance with the regulations of the Occupational Safety and Health Administration (29 CFR, Section 1910.120).

Surface Impoundments —

Surface impoundments are used for the storage, treatment and/or disposal of both hazardous and non-hazardous liquid wastes. Impoundments or lagoons can be constructed either in natural depressions or excavations or created by surface diking. The impoundments typically are used to settle suspended solids. Liquid wastes within the impoundment are usually treated chemically to cause precipitation or coagulation of wastes. Surface impoundments may be either "discharging" or "non-discharging." Discharging impoundments are designed to intentionally permit the supernatant fluid to overflow into receiving streams for final treatment and disposal. Non-discharging impoundments can either intentionally or unintentionally lose liquids through seepage into the subsurface or through evaporation.

The size of a surface impoundment can range from a fraction of an acre to thousands of acres in surface area. The depths of these impoundments reportedly range from 2 feet to more than 30 feet below the ground surface (Office of Technology Assessment, 1984). The specific design and operation requirements for surface impoundments that contain hazardous materials are regulated under RCRA (40 CFR, Parts 264 and 265, Subpart K). To prevent waste infiltration, hazardous waste impoundments are subject to minimum federal technological guidelines for a "compacted soil double liner system" (including compacted, low permeability soil and a single flexible synthetic liner). A leachate collection system is also required to contain any leachate that does infiltrate into the subsurface.

Hazardous waste impoundments are subject to the same minimum federal ground-water protection and monitoring regulations discussed above for hazardous waste landfills. Water levels in monitoring wells located too close to impoundments often reflect the effects of mounding on the water table and lead to inaccurate interpretation of the water-level data (Beck, 1983). The design depth of the monitoring wells also depends on the depth of the bottom of the surface impoundment below ground level and the depth of the first water-bearing zone underlying the bottom of the impoundment.

Waste and Material Piles —

Large quantities of both wastes and materials may be stockpiled for storage. Stockpiled material may include potentially hazardous material such as highway deicing salts, copper, iron, uranium and titanium ore, coal, gypsum and phosphate rock. Hazardous waste piles can also be generated by other industrial operations and vary in composition. Waste piles typically include two types of mining wastes: 1) spoil piles and 2) tailings. Spoil piles are the overburden or waste rock removed during either surface or underground mining operations. Tailings are the solid wastes generated from the cleaning and extraction of ores. Both types of mining waste include waste rock that can contain potential contaminants such as uranium, copper, iron, sulfur and phosphate. Waste piles containing hazardous wastes are regulated under RCRA and are subject to minimum federal design and operational requirements (40 CFR, Parts 264 and 265, Subpart L) and ground-water protection requirements (40 CFR, Part 264, Subpart F), particularly where the waste piles are unprotected from precipitation and surface drainage. In many instances, waste and material piles remain uncovered and exposed to the atmosphere. Precipitation percolating through the material can dissolve and leach potentially hazardous constituents into the subsurface. For example, ground-water quality problems have occurred due to the dissolution of unprotected stockpiles of highway deicing salt. Cyanide leaching to extract gold from mine tailings is potentially dangerous and a widespread problem in some areas. Surface runoff from stockpiles can also be a source of potential ground-water contamination. Ground-water monitoring efforts in waste and material pile areas need to be designed to detect or assess ground-water contamination occurring onsite and to determine that surface runoff has not contaminated adjacent areas.

Land Treatment —

Land treatment involves the application of waste liquids and sludges onto the ground surface for biological or chemical degradation of the waste or for the beneficial use of nutrients contained in the waste. Land treatment operations commonly involve spray irrigation or land spreading of sludges on agricultural, forested or reclaimed land. Municipal wastewater or sludge application to agricultural land is the most common form of land treatment. Industrial waste sludge includes effluent treatment waste, stack scrubber residue, fly ash, bottom ash and slag (Office of Technology Assessment, 1984). Control measures must be instituted to prevent surface runoff, wind erosion and excessive percolation into the ground water during site operation. The rate and duration of sludge application depends on the waste, soil type and the level of anticipated degradation.

Wastes applied to the ground surface at a land treatment facility may be hazardous or non-hazardous. Hazardous waste land treatment facilities are regulated under RCRA and are subject to minimum federal design and operational requirements (40 CFR, Parts 264 and 265, Subpart M) and applicable ground-water protection and monitoring requirements (40 CFR, Parts 264 and 265, Subpart F).

Underground Storage Tanks —

Underground storage tanks are used to store hazardous and nonhazardous waste, industrial products and raw materials. The primary industrial use for tanks is the storage of fuel oils. It is estimated that half of all steel tanks in use store petroleum products. Both steel and fiberglass tanks are also used to store other products including solvents, acids and technical grade chemicals.

Recent amendments to RCRA now specify design, maintenance and operation requirements for tanks containing hazardous waste and commercial petroleum products (40 CFR, Parts 264 and 265, Subpart J). These regulations include requirements for a double liner system and/or cathodic protection of steel tanks, leak detection and inventory control.

Radioactive Waste Disposal Sites —

Radioactive wastes are produced during the development and generation of nuclear fuel and other radioactive materials. Waste products include: 1) spent fuel from nuclear power plant operations, 2) high-level radioactive waste from initial processing of reactor fuels, 3) transuranic waste from fuel processing, 4) low-level wastes from power plants, weapons production, research and commercial activities and 5) medical waste (Office of Technology Assessment, 1984).

The radioactive waste disposal method depends on the radiation levels and the waste characteristics. Low-level radioactive wastes are usually disposed of in shallow burial sites. High-level radioactive wastes are stored in specially constructed facilities and may be reprocessed. Spent reactor fuels may be stored on site or transferred to disposal facilities.

All radioactive waste disposal facilities are regulated by the Nuclear Regulatory Commission. Ground-water monitoring requirements for specific facilities coupled with the design configuration of the facility directly affect the location and installation of monitoring wells.

Waste Characteristics

The physical and chemical characteristics of the waste(s) present at a site should be carefully evaluated and considered together with site hydrogeology when designing a monitoring program. The mechanisms that govern the fate and transport of contaminants in the subsurface affect the occurrence and configuration of a contaminant plume. By considering these effects a monitoring program can be designed to monitor or detect subsurface contamination. The monitoring well locations, the depth of the screened intervals, the method of well installation and the appropriate construction materials must all be compatible with the specific waste and hydrogeological characteristics of the site.

Two physical properties that affect transport and fate of a compound in the subsurface are the relative solubility and density of the contaminant. Based on these properties, contaminants can be classified into categories that subsequently influence monitoring well design: 1) compounds that are primarily miscible/soluble in ground water and 2) compounds that are relatively immiscible/insoluble in ground water. These categories can be further subdivided based on the relative density of the compound.

Primarily Miscible/Soluble Contaminants —

This category of contaminants exhibits a relatively high solubility in water and typically is mobile in the subsurface. Soluble contaminants can exhibit densities greater than, less than or equal to water. In general, where the density of the contaminant closely approximates that of water, the contaminant moves in the same direction and with the same velocity as ground water.

The primary processes that affect dissolved contaminant transport in porous media include advection and dispersion (Freeze and Cherry, 1979; Anderson, 1984; Mackay et al., 1985). Advection is the process by which solutes are transported by the motion of ground water flowing in response to hydraulic gradient, where the gradient reflects the magnitude of the driving force. Dispersion refers to the dispersal of contaminants as they move with the ground water. Dispersion occurs by mechanical mixing and molecular diffusion. Seasonal changes in gradient may affect lateral movement of a contaminant more than dispersion. Interactions that occur between the contaminant and the porous media include retardation, sorption (Freeze and Cherry, 1979; Cherry et al., 1984; Mabey and Mill, 1984; Mackay et al., 1985) and biodegradation (McCarty et al., 1981; McCarty et al., 1984; Wilson et al., 1985). These mechanisms can affect the rate of movement of a contaminant plume or alter the chemistry within the plume.

The effects of contaminant density must also be considered in waste characterization (Bear, 1972). Figure 16 illustrates the migration of a high density, miscible contaminant in the subsurface. As shown, the contaminant sinks vertically through the aquifer and accumulates on top of the lower permeability boundary. The contaminant then moves in response to gravity and follows the topography of the lower permeability boundary, possibly in opposition to the direction of regional ground-water flow. Because the contaminant is also soluble, the contaminant will concomitantly move in response to the processes of advection and dispersion. Therefore, two or more zones of different concentration may be present within the plume: 1) a dense pool of contaminant at the bottom of the aquifer and 2) a dissolved fraction that moves with the ground water. Because the dense, pooled portion of the plume is also soluble, the contaminants will continue to dissolve and migrate in response to ground-water flow conditions. Ground-water monitoring wells installed in the aquifer may more easily detect the dissolved portion of the plume unless a specific monitoring program is devised for the dense phase of the plume. A knowledge of subsurface topography, determined from a top-of-bedrock map or overburden thickness maps and confirmed by surface geophysics and/or borings assist in accurately locating and monitoring the denser portion of the plume.

Figure 17 illustrates the migration of a low density, soluble contaminant. The contaminant initially accumulates at the top of the water table. Dissolution and dispersion of the contaminant occurs as the accumulated contaminant migrates with the ground water. Continued dissolution of the contaminant causes eventual dissipation of the plume. Monitoring for contaminants with these characteristics is frequently most effective in the shallow portion of the aquifer.

Contaminants with a density similar to water migrate in response to advection and dispersion. Contaminants in this category include inorganic constituents such as trace metals and nonmetals. Because of the similarity of contaminant movement to the ground-water movement, certain nonmetals, such as chloride, are commonly used as tracers to estimate the bound-

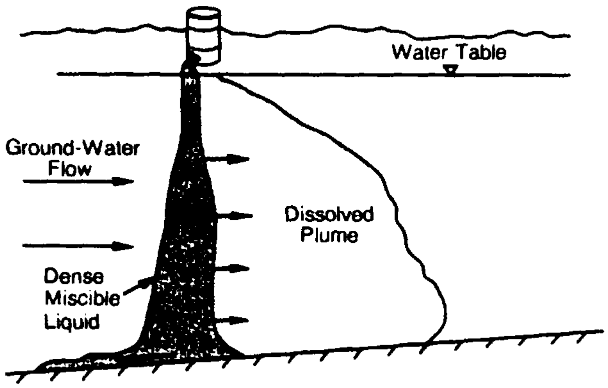


Figure 16. Migration of a high density, miscible contaminant in the subsurface.

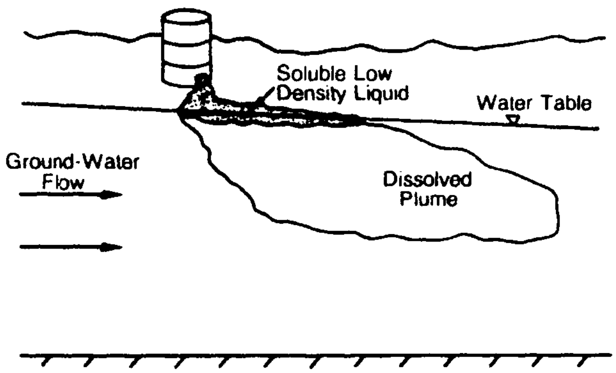


Figure 17. Migration of a low density, soluble contaminant in the subsurface.

aries of contaminant plumes. The dissolved portion of certain organic contaminant plumes can also have a density similar to water and migrate with the ground water. Monitoring and detection schemes for plumes of these contaminants must be based on the calculated effects of advection, dispersion, chemical attenuation and subsurface hydrogeology.

Relatively Immiscible/Insoluble Contaminants —

In both the saturated and unsaturated zones, immiscible compounds exist as either free liquids or as dissolved constituents depending on the relative solubility of the contaminant. The migration of dissolved constituents in the aqueous phase is primarily governed by the processes of advection-dispersion and biological/chemical attenuation (Schwarzenbach and Giger, 1985). The distribution of free liquids is complexly interrelated to capillary pressure, density (gravitational forces) and viscosity (shear forces) (Kovski, 1984; Villaume, 1985). The relative density of the contaminant affects the occurrence and movement of the contaminant in the subsurface and must be considered when locating monitoring wells and when determining the interval(s) to be screened in the aquifer.

Figure 18 illustrates the migration of a low density, immiscible contaminant. The contaminant moves downward through the vadose zone and accumulates at the top of the water table and/or within the capillary fringe. A residual amount of fluid is retained in the vadose zone in response to surficial and interstitial forces (Kovski, 1984; Yaniga and Warburton, 1984). The contaminant plume accumulates on the water table and typically elongates parallel to the direction of ground-water flow (Gillham et al., 1983). The movement and accumulation of immiscible hydrocarbons in the subsurface has been discussed by Blake and Hall (1984), Kovski (1984), Yaniga and Warburton (1984), and Hinchee and Reisinger (1985). Depending on the physical properties of the contaminant, a volatile gas phase may accumulate in the unsaturated zone.

Monitoring wells designed to detect or assess low density immiscible contaminants should be screened in the upper part of the aquifer. In many instances the screen should span the vadose zone and the upper portion of the aquifer to allow the floating contaminant to enter the well. Many immiscible contaminants depress the water table in the well and create an apparent free liquid thickness that is greater than the thickness of the floating contaminant within the aquifer. Where volatiles accumulate in the vadose zone, an explosion hazard may exist. Various mapping and detection techniques including soil-gas sampling and geophysical techniques can be utilized in planning the monitoring well locations to intercept the plume and reduce the risk of an explosion (Noel et al., 1983; Andres and Canace, 1984; Marrin and Thompson, 1984; Saunders and Germeroth, 1985; Lithland et al., 1985).

High density immiscible fluids are called dense non-aqueous phase liquids (DNAPLs). DNAPLs include most halogenated hydrocarbons and other aliphatic compounds because the density of most organic compounds is significantly greater than water. A density difference of one percent or greater has been shown to cause migration of contaminants in the subsurface (Mackay et al., 1985).

Figure 19 illustrates the movement of DNAPLs in the subsurface. Movement of DNAPLs in the unsaturated zone is primarily governed by capillary forces and density (Villaume, 1985). The contaminant sinks through the aquifer and pools at the bottom of the aquifer on top of the lower permeability boundary (Schwille, 1981). The pool of contaminant migrates in response to the topography of the lower permeability boundary independent of regional ground-water flow. Residual material is retained in the pore space of the unsaturated and saturated zones. This residual typically occurs as discrete fingers of globules. The formation and movement of the globules in the subsurface depends on the extant pore-size distribution and capillary forces (Schwille, 1981; Villaume, 1985). As much as five percent by volume of a compound may be retained in the aquifer after plume migration.

Both residual contaminant and the contaminant plume may continue to contribute dissolved constituents to the ground water for an extended period of time. Thus, small spills of persistent compounds have the ability to extensively contami-

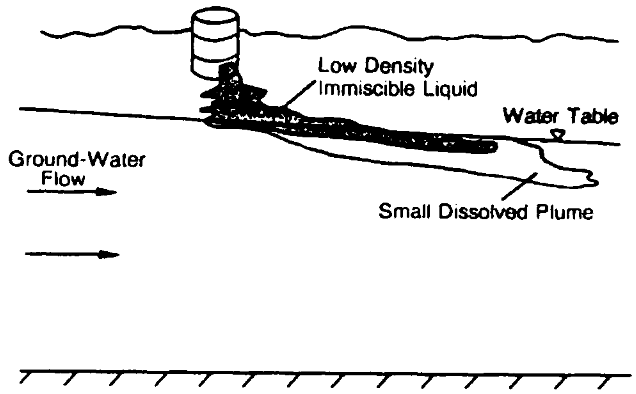


Figure 18. Migration of a low density, immiscible contaminant in the subsurface.

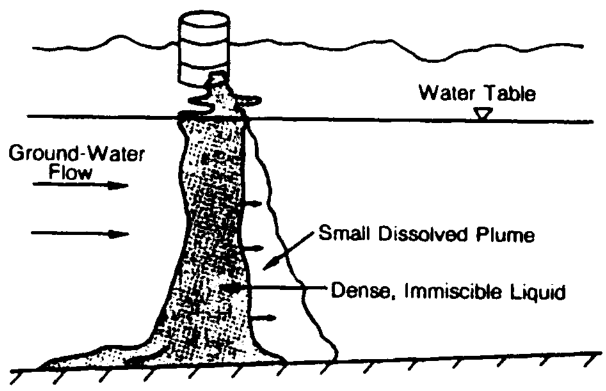


Figure 19. Migration of a dense, non-aqueous phase liquid (DNAPL) in the subsurface.

nate ground water. A vapor plume from the contaminant source may also form and migrate in the vadose zone. These plumes can often be detected through soil-gas sampling techniques.

Field investigations at hazardous waste sites have supported the phenomena of sinking DNAPLs as demonstrated by Schwille (1981) in physical model experiments (Guswa, 1984; Reinhard et al., 1984; Villaume, 1985). Monitoring for these DNAPLs poses special problems. The actual contaminant plume may migrate independently of regional ground-water flow and may be very difficult to locate. Analysis of maps of aquifer thickness and bedrock topography will aid in determining potential migration pathways. The dissolved constituents will migrate according to the ground-water flow regime. Vapor plumes can be detected by using soil-gas sampling techniques.

Villaume (1985) indicates that monitoring well installation through DNAPL-contaminated zones should proceed with caution to avoid cross contamination. Where the borehole is open during drilling or where the annulus is not properly sealed, DNAPLs may migrate down the hole or annulus and cause cross contamination.

Other Anthropogenic Influences

The hydrogeology of a site and the characteristics of the facility are primary factors that should be assessed when choosing specifications for a monitoring well program. However, a variety of factors that relate to the activities of man also should be assessed to determine any potential impacts to the monitoring program. These factors can affect ground-water gradients and flow direction and might have had past impacts on ground-water quality that will affect a current monitoring program.

To minimize the possibility of unknown anthropogenic influences, any initial investigation should include a detailed review of the site history. This review should encompass a study of any land use prior to the current or proposed activity at the site. Additionally, a design and operational history for any existing operation also should be compiled that includes the location of all site activities and the type(s) of waste accepted during the operation of the disposal facility. For example, information about tank age, volume of product delivered and sold, location of the tank and similar information is needed to assess a gasoline-dispensing cooperation. Another example is where a presently regulated disposal facility is located on the site of a previously unregulated landfill or a turn-of-the-century industrial facility. Prior waste disposal practices may already have caused ground-water contamination. Knowledge of the past site practices might lead the investigator to the conclusion that contaminants are held in the vadose zone and could be periodically released to the ground-water during recharge events (Pettyjohn, 1976 and 1982). Cyclic fluctuations in ground-water quality are sometimes difficult to evaluate because naturally-occurring constituents in the vadose zone can also cause similar fluctuations. Additional sources of data to assess site history include: 1) historical photographs, 2) air photos, 3) zoning plats, 4) interviews with local citizens and 5) local newspapers.

A complete site assessment must frequently include an investigation outside the legal boundary of the property. An evaluation of past and present land use practices in the area to be monitored can alert the investigator to potential contamination problems not related to the activity to be monitored. For example, non-point sources such as agricultural practices may affect natural background water quality. Adjacent industrial or commercial facilities may also influence background water quality or may serve as a source of contamination.

Pumping or injection wells near an area to be monitored can affect ground-water flow direction and velocity and/or can influence ground-water quality. The presence of a well or collection of wells with resultant cones of depression or impression might reverse anticipated ground-water flow directions or alter the rate of migration of contaminant plumes. The influence of a pumping well(s) should be determined before completing final design of the monitoring program. Collection of water-level measurements and evaluation of pump test data and velocity plots can be used to determine the possible hydraulic effects of the other wells in the monitoring program (Keely and Tsang, 1983). A more detailed discussion of monitoring strategies that are useful near well fields can be found in Keely (1986). Potential water-quality effects from injection wells near the site must also be evaluated.

Other activities that can alter ground-water velocity and/or direction include infiltration galleries and ground-water recharge facilities. Mounding of the water table beneath these areas will locally affect ground-water gradients. Where the quality of the recharge water differs from background water quality, the ground-water quality in the area may also be affected.

Storm sewers, surface runoff catchments, sanitary sewers, buried underground cables, underground pipelines or other subsurface disturbances may affect ground-water flow paths and ground-water quality. Preferential flow paths can be created when subsurface trenches or excavations are refilled with unconsolidated backfill and bedding materials. These more permeable materials provide conduits that can influence or control the flow of contaminants in the subsurface and can also serve as a vapor migration pathway. Storm and sanitary sewer lines and other buried pipelines may be a source of contamination if leakage occurs. The precise location of buried pipelines and cables should be determined to avoid inadvertently drilling into or through the lines. For example, drilling into natural gas pipelines poses an immediate health and safety risk to anyone near the drilling site. Drilling into pipelines for sanitary or storm sewers poses less of a safety risk, but may exacerbate the contamination problem. In summary, a review of all site activities and subsurface structures serves to contribute valuable information to the monitoring program.

Equipment that the Well Must Accommodate

The purpose of a monitoring well is to provide access to a specific zone from which water-level measurements and/or ground-water quality samples, representative of the extant water quality in the monitored zone, can be obtained. These conditions and the size of equipment necessary to obtain the desired measurements or collect the desired samples will determine the diameter of the well that must be drilled. For example, if the transmissivity of the monitored zone is to be evaluated, then the well diameter must accommodate a pump or other device capable of providing the necessary water demand to make the transmissivity determination. Similarly, if representative ground-water quality samples are to be collected from the well, then an appropriate well diameter must be selected that accommodates the needed sampling equipment. Equipment and procedures that influence the choice of a well diameter include: 1) borehole geophysical tools and downhole cameras, 2) water-level measuring devices, 3) ground-water sampling devices and 4) aquifer testing procedures.

Borehole Geophysical Tools and Downhole Cameras

Use and Limitations of Borehole Geophysical Tools —

Borehole geophysical methods are often used in monitoring wells to obtain hydrogeologic information. Under appropriate conditions, porosity, hydraulic conductivity, pore fluid electrical conductivity and general stratigraphic logs can be obtained. Unfortunately, borehole geophysical methods are frequently limited by the materials and the drilling and completion methods used to construct the well. If it is anticipated that borehole geophysical methods will be conducted in a well, it is necessary to consider the limitations that are imposed by the various methods and materials that are used to construct the well.

Virtually all borehole methods that are likely to be used in shallow ground-water investigations can be conducted in a 2-inch diameter well. Four things that commonly restrict the use of borehole methods are well fluid, casing type, perforation type and gravel pack. Each one of these imposes limitations on the geophysical methods that can be conducted in the well. A summary of the limitations is presented in Table 3, and the limitations are discussed below.

Some geophysical methods require that a fluid be present in the well. Sonic tools will not operate in an air-filled borehole because the acoustic source and receivers are not coupled to the formation. Television systems can operate in air or fluid, but only if the fluid is not murky. Radiometric methods, such as natural gamma, gamma density or neutron moisture logs can operate in air or fluid-filled wells. However, the calibration of these tools is different between air and fluid-filled wells.

Standard resistivity tools that measure the electrical conductivity of the formation will not operate in air-filled boreholes because of the lack of an electrical connection between the electrodes and the formation. Some individuals have modified resistivity tools to operate in air-filled boreholes by altering the electrode design to insure that the electrode is always in contact with the formation. If the well fluid electrical conductivity is two orders of magnitude or more greater than the formation electrical conductivity (electrical conductivity is the reciprocal of electrical resistivity), then the lateral and normal electrical resistivity tools cannot be used because the well fluid distorts the electric field to such a degree that it cannot be corrected. This situation can occur in low porosity formations. The induction log, which measures formation electrical conductivity by electromagnetic coupling, does not require fluid in the well to operate and is usually not affected by the well fluid.

The casing material also influences which methods can be used. No measurement of the electrical properties of the formation can be made if the well is cased with metal. Quantitative resistivity measurements can only be made in open boreholes; limited qualitative measurements can be made in perforated PVC or perforated teflon wells. The formation electrical conductivity can be measured qualitatively with induction logs in wells cased with PVC or teflon. Sonic methods have not been demonstrated to be useful in cased wells, although this is an area that is currently being researched. The calibration of radiometric logs is affected by the thickness and material used in the casing. This is particularly true when neutron moisture methods are used in PVC casing because the method is unable to distinguish hydrogen in the PVC from hydrogen in the pore fluid.

The type of perforations influence which methods can be used. Qualitative resistivity measurements can be made in nonmetallic wells that are uniformly perforated, but not in wells that

Table 3. Use and Limitations of Borehole Geophysical Tools (K. Taylor, Desert Research Institute, Reno, Nevada, Personal Communication, 1988)

	Fluid		Casing Material			Perforations			
Borehole Method	Air	Water	Open	Metal	Plastic	Screen	No Screen	Radius of Investigations (cm)	Comments
Sonic	4	1	1	4	4	4	4	5-50	
Resistivity	4	1	1	4	3	3	4	5-400	
Induction	1	1	1	4	1	1	1	100-400	
Natural Gamma	2	2	2	2	2	1	1	5-30	
Gamma Density	2	2	2	2	2	1	1	5-15	
Neutron	2	2	2	2	2	1	1	5-15	Big effect with PVC
Caliper	1	1	1	1	1	1	1	0	
TV	1	2	1	1	1	1	1	0	Clear fluid only
Borehole Fluid Fluid Resistivity	4	1	1	1	1	1	1	0	
Vertical Flow	4	1	1	1	1	1	4	0	
Horizontal Flow	4	1	1	1	1	3	4	2-6cm	Strongly influenced by screen

[1] Works, this well property does not adversely affect the log
[2] Works, but calibration affected
[3] Works qualitatively
[4] Doesn't work

are not perforated because there is no path for the current between the electrodes and the formation. Vertical flow in the well is controlled by the location of perforated intervals. Hence, the location of perforations will dictate what intervals can be investigated. Horizontal flow through the well is controlled by the radial distribution of perforations. Attempts to measure the horizontal flow must have perforations that are continuous around the well.

In cased holes, the material in and the size of the annulus between the casing and the undisturbed formation will influence geophysical measurements. This occurs because all borehole geophysical measurements are a weighted average of the property being investigated over a cylinder portion of the formation adjacent to the borehole. The radius of this cylinder is referred to as the radius of investigation. The radius of investigation is a function of the geophysical method, tool design, and, to a lesser degree, the formation and annular material. Table 3 lists typical radii of investigation for common borehole geophysical methods. Because it is generally the formation, not the material in the disturbed zone, that is of interest, it is important to ensure that the radius of investigation is larger than the disturbed zone.

The radius of investigation for the sonic tool is on the order of a few wavelengths of the sonic pulse. Hence, it is less for high frequency tools (greater than 30 kHz) than for low frequency tools (less than 20 kHz). The radius of investigation of resistivity tools is controlled by the type of array that is used. Resistivity tools with multiple radii of investigation can commonly be used to correct for the effects of a disturbed annulus. The radiometric logs have a very limited radius of investigation and usually require a driven casing or open borehole to be accurate. The spacing between the source and the detector influences the radius of investigation. Some tools use two spacings to correct for disturbed zones less than approximately 4 inches in radius. Horizontal flow through the borehole is strongly affected by the hydraulic conductivity of the material in the disturbed zone. Hydraulic testing of discrete intervals with straddle packers is adversely affected if the annular material adjacent to the packers has a hydraulic conductivity significantly greater than the formation.

When using tools that have a radioactive source (gamma density or neutron moisture), state regulations vary. Most states severely restrict the use of these tools in water wells. At a minimum, it is usually required that the measurements be made in cased wells. This complicates the use of these tools because the casing influences the calibration and creates a disturbed zone. Another common restriction is that the well not be perforated in an aquifer with potable water. This further limits the use of these methods to areas that are already contaminated.

General Applications —

Natural gamma and self potential (SP) logs are commonly used to detect lithologic boundaries and to identify formations containing clays and shales (Keys, 1968; Keys and MacCary, 1971; Voytek, 1982; Mickam et al., 1984; Taylor et al., 1985). Both natural gamma and SP logging tools can be accommodated by 2-inch diameter or larger wells and are frequently available in combination with other logging tools as a portable unit that may be easily transported to sites with restricted access.

Formation porosity and density may be determined through the use of neutron, sonic and gamma-gamma logs (Keys, 1968; Keys and MacCary, 1971; Senger, 1985). The use of the neutron tool is generally accepted as an indicator of moisture content (Keys, 1968). Wilson (1980) and Everett et al. (1984) have pointed out limitations in using the neutron tool inside plastic casing, in the presence of certain contaminants and in certain geologic settings. Tool detector sizes are limited to 2-inch diameter wells or greater and are available as portable units for remote field access.

Various types of caliper logs are used to maintain a continuous record of well or borehole diameter that can be used to detect broken casings, the location of fractures, solution development, washed-out horizons and hydrated clays (Keys and MacCary, 1971; Mickam et al., 1984; DeLuca and Buckley, 1985). Diameters are "sensed" through the use of multiple feeler arms or bow springs. Calipers are available for borehole or well diameters ranging from 1.65 inches to 30 inches.

Other borehole logging tools may be used to derive information about the character of water in the borehole and the formation. Induction tools are used to measure pore fluid conductivity (Taylor et al., 1985). Selected resistivity tools with different formation penetration depths are used to detect variations in pore fluids (Keys, 1968; Keys and MacCary, 1971; Kwader, 1985; Lindsey, 1985). Temperature logs have recently been applied to the detection of anomalous fluid flow (Urban and Diment, 1985). Induction, resistivity and temperature logging tools have been designed to fit 2-inch diameter or larger monitoring wells.

Flowmeters are used to monitor fluid rates in cased or uncased holes. This tool provides direct ground-water flow measurement profiling. Flowmeters can also be used to detect thief zones, lost circulation zones and the location of holes in casing. Flowmeters measure flow using low inertia impellers or through changes in thermal conductance as liquids pass through the tool (Kerfoot, 1982). Many professionals remain unconvinced, however, as to the effectiveness of flowmeters. Impeller flowmeters are available as small as 1.65 inches in diameter; conductance flowmeters are typically 1.75 inches in diameter.

Some uncertainty exists in the application of almost all borehole equipment including geophysical logs. The correct interpretation of all such data often depends on precise knowledge of geologic and hydrogeologic conditions that are frequently not available. Therefore the interpretation of these data are invariably subjective.

Downhole television cameras can be used to gather in-situ information on boreholes and monitoring wells (Huber, 1982; Morahan and Doorier, 1984). Television logging may be used to check monitoring well integrity (i.e., casing and screen damage), to inspect installation and construction procedures and to accurately characterize subsurface fractures and geologic strata. Borehole television cameras have recently become available for wells as small as 2 inches in diameter. Cameras are available that provide multi-angle viewing, black/white or color images and recorded depth data during imaging.

Many of the logging tools discussed in this section are available as either combination probes or single probes. These tools have been designed so that they can be run from truck mounted winches and loggers or from portable units that can be transported by backpack to sites where vehicular access is restricted. In addition, a variety of portable data loggers are available to record logging data gathered onsite.

Water-Level Measuring Devices

The basic water-level measuring device is a steel tape typically coated with ordinary carpenter's chalk. This is the simplest water-level measuring device and is considered by many to be the most accurate device at moderate depths. In addition to a standard steel tape, the five main types of water-level measuring devices are: 1) float-type, 2) pressure transducers, 3) acoustic probes, 4) electric sensors and 5) air lines. Float-type devices rest on the water surface and may provide a continuous record of water levels on drum pen recorders or data loggers. Float sizes range from 1.6 inches to 6.0 inches in diameter, but are only recommended for wells greater than 4 inches in diameter due to loss of sensitivity in smaller diameter boreholes. Pressure transducers are suspended in the well on a cable and measure height of water above the transducer center. Transducers are available in diameters as small as 0.75 inches. Acoustic well probes use the reflective properties of sound waves to calculate the distance from the probe at the wellhead to the water surface. Acoustic probes are designed for well diameters as small as 4 inches and are limited to water depths greater than 25 feet (Ritchey, 1986). Electric sensors are suspended on the end of a marked cable. When the sensor encounters conductive fluid, the circuit is completed and an audible or visual signal is displayed at the surface. Air lines are installed at a known depth beneath the water; and by measuring the pressure of air necessary to discharge water from the tube, the height of the water column above the discharge point can be determined.

Steel tapes coated with a substance that changes color when wetted are also used as water-level measuring devices (Garber and Koopman, 1968). Tapes are available as small as 0.75 inches in width. Specially coated tape with physical and chemical resistance has recently been developed that is 0.375 inches in width and contains electrical conductance probes at the end of the tape to sense water levels (Sanders, 1984).

Ground-Water Sampling Devices

A wide variety of ground-water sampling devices are available to meet the requirements of a ground-water monitoring program. A discussion of the advantages and disadvantages of sampling devices is provided by Barcelona et al. (1983) and (1985a), Nielsen and Yeates (1985) and Bryden et al. (1986).

Bailers are the simplest of the sampling devices commonly used for ground-water sampling. They can be constructed from a variety of materials including polytetrafluorethylene (PTFE), polyvinyl chloride (PVC) and stainless steel. Diameters of 0.5 inches or larger are common. Because bailers are lowered by hand or winch, the maximum sampling depth is limited by the strength of the winch and the time required for bailing.

Grab samplers such as Kemmerer samplers can be used to collect samples from discrete sampling depths. These samplers can be constructed from a variety of materials and can be manufactured to fit in wells with 0.5-inch diameter or larger.

Syringe samplers allow for depth discrete sampling at unlimited depths while reducing effects on sample integrity (Nielsen and Yeates, 1985). Syringe samplers have been constructed from stainless steel, PTFE and polyethylene/glass with various modifications (Gillham, 1982). These samplers may be utilized in wells with a casing diameter 1.5 inches or larger.

Suction lift or vacuum pumps include both centrifugal and peristaltic pumps. These types of pumps are limited to sampling depths of less than 25 feet. However, they can be utilized in wells of 0.5-inch diameter or larger.

Gas drive samplers can be used in wells with a casing diameter of 0.75 inches or larger. These samplers operate on the principal of applied gas pressure to open/close check valves and deliver samples to the surface (Robin et al., 1982; Norman, 1986). Sampling depth is limited by the internal working strength of the tubing used in sampler construction.

Positive displacement bladder pumps can be constructed of various inert materials for wells with a diameter of 1.5 inches or larger. The use of pressurized bladders ensures that the sample does not contact the driving gas. Most bladder pumps are capable of lifting samples from 300 to 400 feet, although models capable of 1000 feet of lift have been recently advertised.

Both gear-drive and helical rotor submersible pumps have been developed for wells with a casing diameter of at least 2 inches. These pumps are capable of lifts of up to at least 150 feet. Submersible gas-driven piston pumps have been developed that operate on compressed air or bottled gas without contact of the sample with the air. These pumps are available for 1.5 and 2-inch diameter monitoring wells and have pumping lifts from 0 to 1000 feet. All of these types of pumps can be constructed from various inert materials and may provide continuous, but variable flow rates to minimize degassing of the sample.

Aquifer Testing Procedures

The diameter, location, depth, and screened interval of a monitoring well should be chosen based on the need for and the type of aquifer testing procedures that will be performed on the well. Observation wells generally do not have to be designed with the same diameter criteria in mind. The type of aquifer testing procedure should be based on the hydraulic characteristics of the aquifer such as transmissivity, storage coefficient, homogeneity and areal extent.

Pumping tests are typically performed in wells with a high transmissivity and in wells with a diameter large enough to accommodate the pumping equipment. Conversely, slug injection or recovery tests, that add or remove smaller amounts of water, are typically performed in formations with low transmissivity and in smaller diameter wells. Packer tests can be conducted in wells as small as 2 inches in diameter, but the optimum well diameter for packer testing is 4 inches. Bailer tests to evaluate aquifer characteristics can be performed in wells of all diameters. Tracer tests are also used to evaluate aquifer characteristics and can be performed regardless of well diameter.

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Section 3
Monitoring Well Planning Considerations

Recordkeeping

The development of an accurate recordkeeping process to document the construction, installation, sampling and maintenance phases of a monitoring well network plays an integral part in determining the overall success of the program. An accurate account of all phases is necessary to ensure that the goals of the monitoring program (i.e. accurate characterization of the subsurface hydrogeology and representative water-quality samples, etc.) are met. It is from these records that information will be used to resolve any future monitoring problems that will be encountered.

Recordkeeping begins with the drilling of the monitoring well. Complete documentation of the drilling and/or sampling process should be accurately recorded in a field notebook and transferred to a boring log. Notations about weather, drilling equipment, personnel on the site, sampling techniques, subsurface geology and hydrogeology should be recorded. Lithologic descriptions should be based on visual examination of the cuttings and samples and confirmed with laboratory analyses where appropriate. The Unified Soil Classification System is one universally accepted method of soil description. In the Unified Soil Classification System, soils are designated by particle size and moisture content. A description of the system can be found in a publication by the United States Department of Interior (1974). Identification and classification of rock should include typical rock name, notations on pertinent lithology, structural features and physical alterations. Although there is no universally accepted system for describing rock, one system is described by Williamson (1984). A list of information that should be recorded in the field notebook is contained in Table 4. Information in the field notebook is transferred to the boring log for clarity of presentation. Figure 20 illustrates the format for a sample boring log. Both the boring log and the field notes become part of the permanent file for the well.

In addition to the boring log, an "as-built" construction diagram should be drawn for each well. This differs from a "typical monitoring well" diagram contained within the design specifications because the "as-built" diagram contains specific construction information about the materials and depths of the well components. An "as-built" diagram eliminates confusion if the monitoring well was not built exactly as conceived in the design specifications. In addition, the drawing provides an "at-a-glance" picture of how the well is constructed (similar to the function of a boring log). The "as-built" diagram should contain information about the elevation, depth and materials used in well construction. Figure 21 illustrates the format for an "as-built" diagram of a monitoring well.

Finally, records should be kept for *each* well illustrating not only the construction details for the well, but also a complete history of actions related to the well. These include: 1) dates and notations of physical observations about the well, 2) notations about suspected problems with the well, 3) water-level measurements, 4) dates of sample collection (including type of sampler, notations about sample collection and results of laboratory analyses), 5) dates and procedures of well maintenance and 6) date, method and materials used for abandonment. This record becomes part of a permanent file that is maintained for each well.

Decontamination

Decontamination of drilling and formation-sampling equipment is a quality-control measure that is often required during drilling and installation of ground-water monitoring wells. Decontamination is the process of neutralizing, washing and rinsing equipment that comes in contact with formation material or ground water that is known or is suspected of being contaminated. Contaminated material that adheres to the surface of drilling and formation sampling equipment may be transferred via the equipment: 1) from one borehole to another and/or 2) vertically within an individual borehole from a contaminated to an uncontaminated zone. The purpose for cleaning equipment is to prevent this "cross-contamination" between boreholes or between vertical zones within a borehole. Although decontamination is typically used where contamination exists, decontamination measures are also employed in uncontaminated areas as a quality control measure.

Planning a decontamination program for drilling and formation sampling equipment requires consideration of:

1) the location where the decontamination procedures will be conducted, if different from the actual drilling site;
2) the types of equipment that will require decontamination;
3) the frequency that specific equipment will require decontamination;
4) the cleaning technique and type of cleaning solutions and/or wash water needed for decontamination;
5) the method for containing the residual contaminants and cleaning solutions and/or wash water from the decontamination process, where necessary; and
6) the use of a quality control measure, such as equipment blanks or wipe testing, to determine

Table 4. Descriptive Information to be Recorded for each Monitoring Well

General Information

Boring number
Date/time to start and finish well
Location of well (include sketch of location)
Elevation of ground surface
Weather conditions during drilling
Name of driller, geologist and other personnel on site

Drilling Information

Type of drilling equipment
Type and design of drill bit
Any drilling fluid used
Diameter of drill bit
Diameter of hole
Penetration rate during drilling (fee/minute, minutes/foot, feet/hour, etc.)
Depth to water encountered during drilling
Depth to standing water
Soil/rock classification and description
Total well depth
Remarks on miscellaneous drilling conditions, including:
- a) loss or gain of fluid
- b) occurrence of boulders
- c) cavities or voids
- d) borehole conditions
- e) changes in color of formation samples or fluid
- f) odors while drilling

Sampling Information

Types of sampler(s) used
Diameter and length of sampler(s)
Number of each sample
Start and finish depth of each sample
Split spoon sampling:
- a) size and weight of drive hammer
- b) number of blows required for penetration of 6 inches
- c) free fall distance used to drive sampler

Thin-walled sampling:
- a) relative ease or difficulty of pushing sample OR
- b) pounds per square inch (psi) necessary to push sample

Rock cores:
- a) core barrel drill bit design
- b) penetration rate (fee/minute, minutes/foot, fee/hour, etc.)

Percent of sample recovered

Well Completion Information

Elevation of top of casing (± .01 foot)
Casing:
- a) material
- b) diameter
- c) total length of casing
- d) depth below ground surface
- e) how sections joined
- f) end cap (yes or no)

Screen:
- a) material
- b) diameter
- c) slot size and length
- d) depth to top and bottom of screen

Filter pack:
- a) type/size
- b) volume emplaced (calculated and actual)
- c) depth to top of filter pack
- d) source and roundness
- e) method of emplacement

Grout and/or sealant:
- a) composition
- b) method of emplacement
- c) volume emplaced (where applicable) (calculated and actual)
- d) depth of grouted interval (top and bottom)

Backfill material:
- a) depth of backfilled interval (top and bottom)
- b) type of material

Surface seal detail:
- a) type of seal
- b) depth of seal (must be below frost depth)

Well protector:
- a) type
- b) locking device
- c) vents (yes or no)

Well development:
- a) method
- b) date/time; start/stop
- c) volume and source water (if used)

the effectiveness of the decontamination procedure, if appropriate.

The degree to which each of these items are considered when developing a decontamination program varies with the level of contamination anticipated at the site. Where the site is "clean," decontamination efforts may simply consist of rinsing drilling and formation sampling equipment with water between samples and/or boreholes. As the level of anticipated or actual contamination increases, so should the decontamination effort. A document by the United States Environmental Protection Agency (1987) discusses decontamination at CERCLA sites.

One important factor when designing a decontamination program is the type of contaminant(s). The greater the toxicity or the more life-threatening the contaminant, the more extensive and thorough the decontamination program must be. The following discussion focuses on measures to be employed at sites where contamination is known or suspected or decontamination is desired as a quality control measure. Less formally defined decontamination efforts may be employed at any site.

Decontamination Area

An appropriate decontamination area at a site is selected based on the ability to: 1) control access to the decontamination area, 2) control or contain residual material removed from the surfaces of the drilling and formation sampling equipment and 3) store clean equipment to prevent recontamination before use. In addition, the decontamination area should be located in close proximity to the drilling area to minimize further site contamination. The importance of these considerations during the selection process for a decontamination area will be influenced by the type of contaminants involved and the extent of contamination at the site. For example, the decontamination area for drilling and formation sampling equipment may be located near the drilling rig when: 1) the ground surface is regarded as noncontaminated, 2) the known or suspected subsurface contaminants are non-hazardous and 3) the drilling method permits good control over the containment of cuttings from the borehole. However, the decontamination area should be located an adequate distance away from the rig to avoid contamination of clean equipment by airborne lubricating oil or hydraulic fluids from the drilling rig. Once drilling and sampling equipment is cleaned, the equipment should not be placed directly on the ground surface even though the area is generally regarded as noncontaminated. Clean equipment should be placed, at a minimum, on top of plastic ground sheeting, and the sheeting

BORING NO. 2A
SH 1 OF 1

BORING LOG

PROJECT AML Manufacturing DATE START Aug. 30, 1987 FINISH Aug. 31, 1987
LOCATION Sussex County GROUND ELEV. 337.09' TOTAL DEPTH (FT) 23.50'
CASING I.D. 4.25" CORE SIZE NX TYPE Air Rotary w/Casing Hammer
CONTRACTOR Sprowls & Sons LOGGED BY S. Smith

SCALE IN FEET	LITHOLOGIC SYMBOL	SAMPLE TYPE AND NO.	SAMPLE BLOWS OR REC	SAMPLE DEPTH RANGE (FT.)	RQD %	RATE OF PEN MIN/FT.	SOIL AND ROCK DESCRIPTION/COMMENTS (Unified soil class system. Rock description. Depth to water table. Loss of drill fluid, etc.)
						0.5	
5'		SS-1	45-29 -36	5.0' 6.5'	70		Gravelly SILT, little sand, trace clay. About 30% pebbles and granules. Moderately moist. Moderate yellowish brown (10 YR5/4, mottled 5Y5/2); drab Till. [GM]
						0.7	
10'		SS-2	43-45 -56	10.0'- 11.5'	85	Core Breaks	Gravelley SILT, little sand, trace clay. About 30% pebbles and granules. Dry to slightly moist. Moderate yellowish brown (10 YR5/4); drab Till. [GM]
15'		NX-1			5.25'		Medium dark gray to dark gray SILTSTONE, sandy SILTSTONE, with minor shale seams. Fresh and hard except at breaks along slightly to moderately weathered shale seams. Jointed and broken approximately as depicted. Coquina seam (15.1'-15.2'), very calcareous. Generally only calcareous in sandy SILTSTONE layers. Wet @17.5'
20'		NX-2			5.0' 100		Medium dark gray to dark gray SILTSTONE, sandy SILTSTONE, and minor shale seams, same as above.
							End of Boring - Total Depth = 23.50'
25'							Piezometer 2A installed with screened interval of 18.0' to 23.0'

Overburden 13.0'
Rock 10.5'
Total Depth 23.50'

Water Level	16.2'	16.35'
Date	8/30/87	8/30/87
Time	1:00 p.m.	3:00 p.m.
Elevation Measuring Point	Top of Casing	Top of Casing

Comments Surface casing driven 8" into rock.

Figure 20. Sample boring log format (after Electric Power Research Institute, 1985).

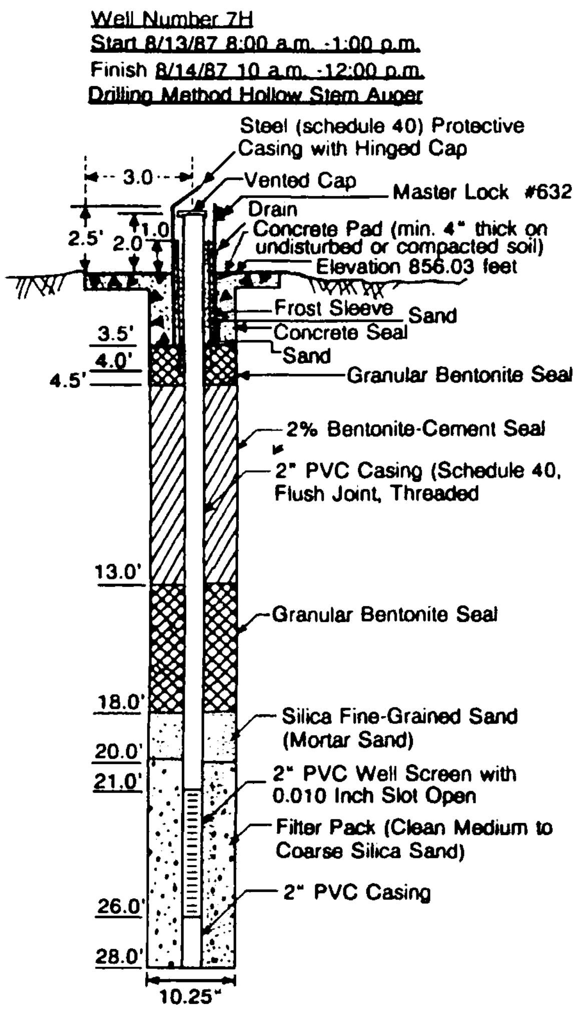

Figure 21. Format for an "as-built" monitoring well diagram.

should be discarded after each borehole is drilled. Clean equipment may also be stored off the ground on storage or equipment racks until used for drilling or formation sampling. Heavy equipment, such as the drilling rig, water truck or any other support vehicle, should be cleaned in the decontamination area prior to demobilizing from the site.

The presence of hazardous materials at a drilling site dictates that a more controlled access area be established for equipment decontamination to prevent cross-contamination and to provide worker safety. Figure 22 shows a general layout of a contaminant reduction zone where systematic decontamination procedures are employed as personnel and equipment move from the hazardous material exclusion zone to a clean, non-hazardous support zone.

Types of Equipment

Decontamination of drilling and formation sampling equipment involves cleaning tools used in the borehole. This equipment includes drill bits, auger sections, drill-string tools, drill rods, split-barrel or thin-wall tube samplers, bailers, tremie pipes, clamps, hand tools and steel cable. Equipment with a porous surface, such as natural rope, cloth hoses and wooden blocks or handles, cannot be thoroughly decontaminated and should be disposed of properly after completion of the borehole. The specific drilling and formation sampling equipment that needs to be cleaned should be listed in the equipment decontamination program.

A decontamination program for equipment should also include cleaning heavy equipment, including the drill rig and support trucks. Advanced planning is necessary to ensure that the decontamination area is adequately sized to accommodate large vehicles, and that any contaminants removed from the vehicles are properly controlled and contained within the decontamination area. This should include the "tracking zone" created by vehicles as they move into and out of the area.

Frequency of Equipment Decontamination

A decontamination program for equipment should detail the frequency that drilling and formation sampling equipment is to be cleaned. For example, drilling equipment should be decontaminated between boreholes. This frequency of cleaning is designed to prevent cross-contamination from one borehole to the next. However, drilling equipment may require more frequent cleaning to prevent cross-contamination between vertical zones within a single borehole. Where drilling equipment is used to drill through a shallow contaminated zone and to install surface casing to seal-off the contaminated zone, the drilling tools should be decontaminated prior to drilling deeper. Where possible, field work should be initiated by drilling in that portion of the site where the least contamination is suspected.

Formation sampling equipment should be decontaminated between each sampling event. If a sampling device is not adequately cleaned between successive sampling depths, or between boreholes, contaminants may be introduced into the successive sample(s) via the formation sampling device.

Cleaning Solutions and/or Wash Water

Decontamination of equipment can be accomplished using a variety of techniques and fluids. The most common and generally preferred methods of equipment decontamination involve either a clean potable water wash, steam cleaning or water/wash steam cleaning combination. Water washing may be accomplished using either low or high pressure. If a low pressure wash is used, it may be necessary to dislodge residual material from the equipment with a brush to ensure complete decontamination. Steam cleaning is accomplished using portable, high-pressure steam cleaners equipped with pressure hose and fittings.

Sometimes solutions other than water or steam are used for equipment decontamination. Table 5 lists some of the chemicals and solution strengths that have been used in equipment decontamination programs. One commonly used cleaning solution is a non-phosphate detergent. Detergents are preferred over other cleaning solutions because the detergent alone does not pose a handling or disposal problem. In general, when a cleaning solution for equipment decontamination is necessary, a non-phosphate detergent should be used unless it is demonstrated that the environmental contaminant in question cannot be removed from the surface of the equipment by detergents.

Acids or solvents should be used as cleaning solutions only under exceptional circumstances because these cleaners are, in

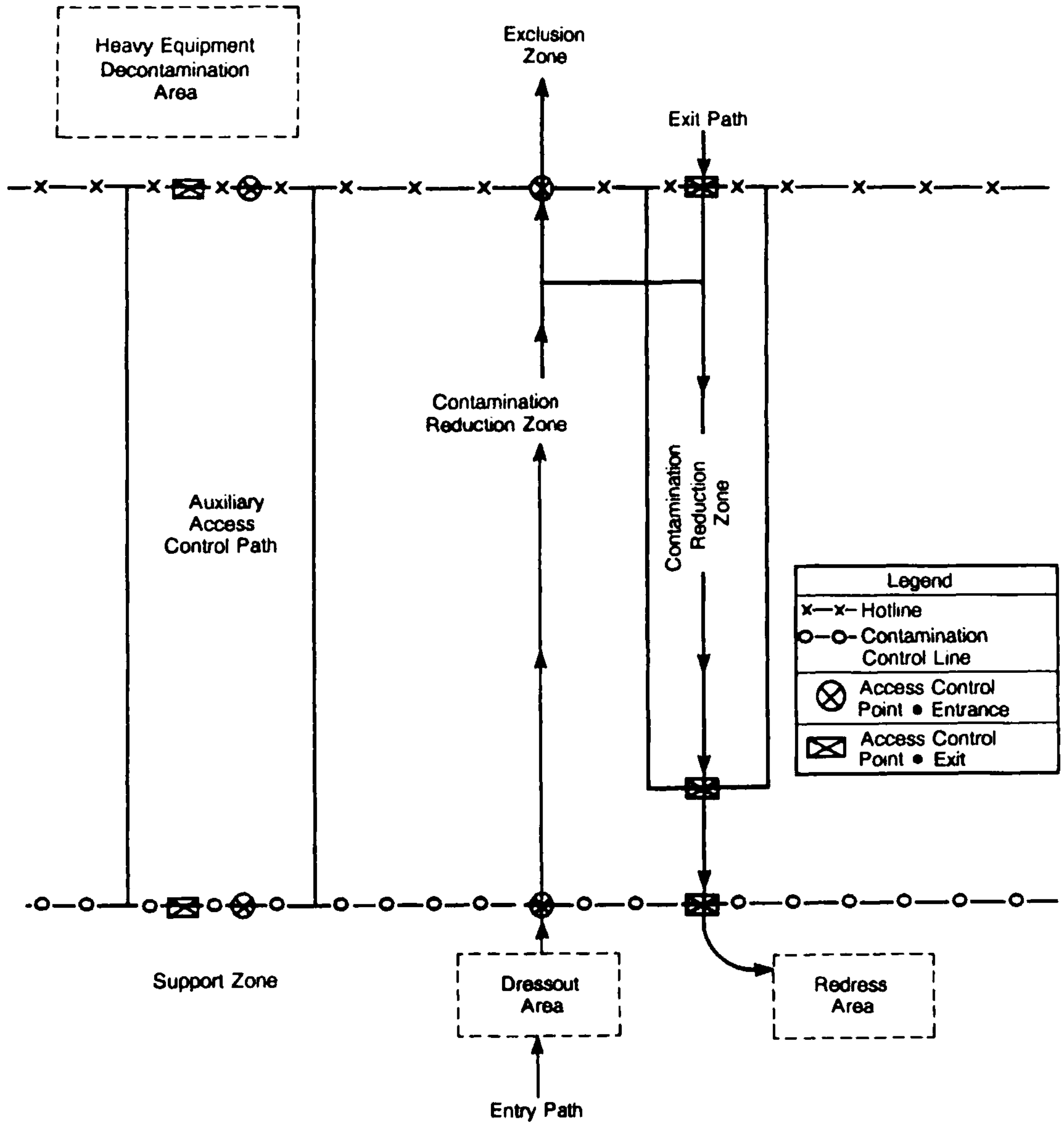

Figure 22. Typical layout showing decontamination areas at a hazardous materials site (United States Environmental Protection Agency, 1984).

and of themselves, hazardous materials and may serve as contaminants if introduced into the borehole. When using chemical solutions for equipment decontamination, water or steam should always be used as a final rinse to remove any residual chemical cleaner from the surface of the equipment and thereby prevent contamination of the borehole by the cleaning solution.

According to Moberly (1985), a typical sequence for decontamination of low to moderately contaminated equipment might include:

1) water or steam rinse to remove particulates;
2) steam wash with water or non-phosphate detergent; and
3) steam or water rinse with potable water.

Additional wash/rinse sequences may be necessary to completely remove the contaminants.

Containment of Residual Contaminants and Cleaning Solutions and/or Wash Water

Contaminated material removed from the surfaces of equipment and cleaning solutions and/or wash water used during decontamination usually require containment and proper disposal. If non-hazardous contaminants are involved, the decontamination program for equipment may not require provisions for the disposal of wash water and residual material removed from the equipment. Conversely, a decontamination program for equipment exposed to hazardous materials requires provision for catchment and disposal of the contaminated material, cleaning solution and/or wash water.

Where contaminated material and cleaning fluids must be contained from heavy equipment such as drill rigs and support vehicles, the decontamination area must be properly floored. Preferred flooring for the decontamination area is typically a

Table 5. List of Selected Cleaning Solutions Used for Equipment Decontamination (Moberly, 1985)

Chemical	Solution	Uses/Remarks
Clean Potable Water	None	Used under high pressure or steam to remove heavy mud, etc., or to rinse other solutions
Low-Sudsing Detergents (Alconox)	Follow Manufacturer's Directions	General all-purpose cleaner
Sodium Carbonate (Washing Soda)	4#/10 Gal Water	Effective for neutralizing organic acids, heavy metals, metal processing wastes
Sodium Bicarbonate- (Baking Soda)	4#/10 Gal Water	Used to neutralize either base or neutral acid contaminants
Trisodium Phosphate (TSP Oakite)	2#/1O Gal Water	Similar to sodium carbonate
	4#/10 Gal Water	Useful for solvents & organic compounds (such as Toluene, Chloroform, Trichloroethylene). PBB's and PCB's
Calcium Hydrochloride (HTH)	8#/1O Gal Water	Disinfectant, bleaching & oxidizing agent used for pesticides, fungicides, chlorinated phenols, dioxins, cyanides, ammonia & other non-acidic inorganic wastes
Hydrochloric Acid	1 Pt/10 Gal Water	Used for inorganic bases, alkali and caustic wastes
Citric, Tartaric, Oxalic Acids (or their respective salts)	4#/10 Gal Water	Used to clean heavy metal contamination
Organic Solvents (Acetone, Methanol, Methylene Chloride)	Concentrated	Used to clean equipment contaminated with organics or well casing to remove surface oils, etc

reinforced, curbed, concrete pad which is sloped toward one corner where a sump pit is installed (Moberly, 1985). Where a concrete pad is impractical, planking can be used to construct a solid flooring that is then covered by a nonporous surface and sloped toward a collection facility. Catchment of contaminants and cleaning fluids from the decontamination of lighter-weight drilling equipment and hand tools can be accomplished by using small trenches lined with plastic sheeting or in wash tubs or stick cans. The contaminated cleaning fluids can be stored temporarily in metal or plastic cans or drums until removed from the site for proper disposal.

Effectiveness of Decontamination Procedures

A decontamination program for drilling and formation sampling equipment may need to include quality-control procedures for measuring the effectiveness of the cleaning methods. Quality-control measures typically include either equipment blank collection or wipe testing. Equipment blanks are samples of the final rinse water that are collected after cleaning the equipment. Equipment blanks should be collected in appropriate sampling containers, properly preserved, stored and transported to a laboratory for analyses of contaminants known or suspected at the site. Wipe testing is performed by wiping a cloth or paper patch over the surface of the equipment after cleaning. The test patch is placed in a sealed container and sent to a laboratory for analysis. Laboratory results from either equipment blanks or wipe tests provide "after-the-fact" information that may be used to evaluate whether or not the cleaning methods were effective in removing the contaminants of concern at the site.

Personnel Decontamination

A decontamination program for drilling and sampling equipment is typically developed in conjunction with health and safety plans for field personnel working at the site. Although a discussion of site safety plans and personnel protective measures are beyond the scope of this manual, the health and safety plan for field personnel should be of foremost concern when drilling in known or suspected contaminated areas. Specific health and safety procedures necessary at the site depend on the toxicity and physical and chemical properties of known or suspected contaminants. Where hazardous materials are involved or suspected, a site safety program should be developed by a qualified professional in accordance with the Occupational Safety and Health Administration requirements in 29 CFR 1910.120. Field personnel at hazardous sites should receive medical screening and basic health and safety training, as well as specific on-site training.

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Section 4
Description and Selection of Drilling Methods

Introduction

Monitoring wells can be, and have been, installed by nearly every conceivable type of drilling and completion technique. However, every drilling technology has a special range of conditions where the technique is most effective in dealing with the inherent hydrogeologic conditions and in fulfilling the purpose of the monitoring well. For example, constructing wells by driving wellpoints or by jetting provides low-cost water-level information but severely limits the ability to collect detailed stratigraphic information.

The following section contains a description of common methods of monitoring well construction and includes a discussion of the applications and limitations of each technique. A matrix that helps the user determine the most appropriate technology for monitoring well installation in a variety of hydrogeologic settings with specific design objectives is also included in this section.

Drilling Methods for Monitoring Well Installation

Hand Augers

Hand augers may be used to install shallow monitoring wells (0 to 15 feet in depth) with casing diameters of 2 inches or less. A typical hand auger, as shown in Figure 23, cuts a hole that ranges from 3 to 9 inches in diameter. The auger is advanced by turning into the soil until the auger is filled. The auger is then removed and the sample is dumped from the auger. Motorized units for one- or two-operators are available.

Generally, the borehole cannot be advanced below the water table because the borehole collapses. It is often possible to stabilize the borehole below the water table by adding water, with or without drilling mud additives. The auger may then be advanced a few feet into a shallow aquifer and a well intake and casing installed. Another option to overcome borehole collapse below the water table is to drive a wellpoint into the augered hole and thereby advance the wellpoint below the water table. The wellpoint can then be used to measure water levels and to provide access for water-quality samples.

Better formation samples may sometimes be obtained by reducing the hole size one or more times while augering to the desired depth. Because the head of the auger is removable, the borehole diameter can be reduced by using smaller diameter auger heads. Shaft extensions are usually added in 3- or 4-foot increments. As the borehole size decreases, the amount of energy required to turn the auger is also reduced. Where necessary, short sections of lightweight casing can be installed to prevent upper material from caving into the borehole.

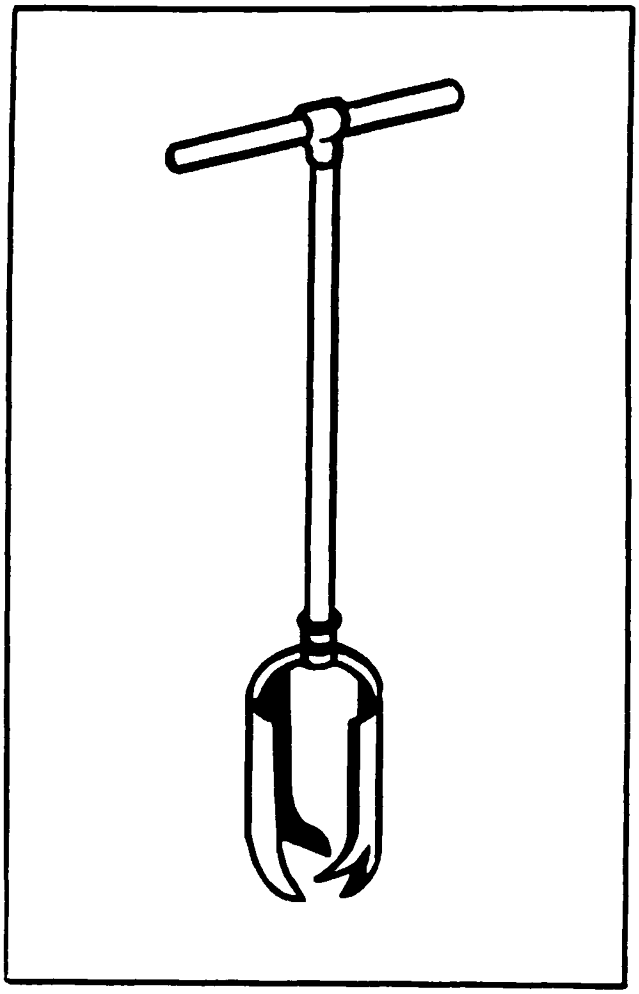

Figure 23. Diagram of a hand auger.

A more complete list of the applications and limitations of hand augers is found in Table 6.

Driven Wells

Driven wells consist of a wellpoint (screen) that is attached to the bottom of a casing (Figure 24). Wellpoints and casing are usually 1.25 to 2 inches in diameter and are made of steel to withstand the driving process. The connection between the wellpoint and the casing is made either by welding or using

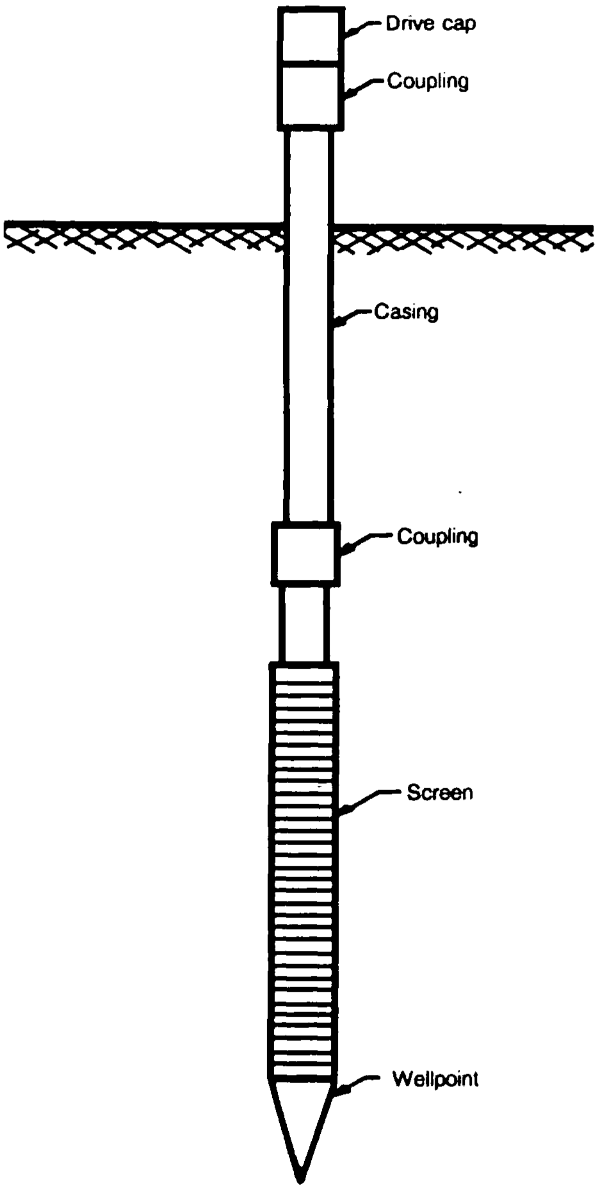

Figure 24. Diagram of a wellpoint.

drive couplings. Drive couplings are specially designed to withstand the force of the blows used to drive the casing; however, if the casing is overdriven it will usually fail at a coupling. When constructing a well, a drive cap is placed on top of the uppermost section of casing, and the screen and casing are driven into the ground. New sections of drive casing are usually attached in 4 or 5-foot sections as the well is driven deeper. Crude stratigraphic information can be obtained by recording the number of blows per foot of penetration as the wellpoint is driven.

Wellpoints can either be driven by hand or with heavy drive heads mounted on a tripod, stiff-leg derrick or similar hoisting device. When driven by hand, a weighted drive sleeve such as is used to install fence posts is typically used. Depths up to 30 feet can be achieved by hand in sands or sand and gravel with thin clay seams; greater depths of 50 feet or more are possible with hammers up to 1,000 pounds in weight. Driving through dense silts and clays and/or bouldery silts and clays is often extremely difficult or impossible. In the coarser materials, penetration is frequently terminated by boulders. Additionally, if the wellpoint is not structurally strong it may be destroyed by driving in dense soils or by encountering boulders. When driving the wellpoint through silts and/or clays the screen openings in the wellpoint may become plugged. The screen may be very difficult to clean or to reopen during development, particularly if the screen is placed in a low permeability zone.

To lessen penetration difficulties and screen clogging problems, driven wells may be installed using a technique similar to that used in cable tool drilling. A 4-inch casing (with only a drive shoe and no wellpoint) may be driven to the targeted monitoring depth. As the casing is driven, the inside of the casing is cleaned using a bailing technique. With the casing still in the borehole, a wellpoint attached to an inner string of casing is lowered into the borehole and the outer casing is removed. As the casing is removed, the well must be properly sealed and grouted. A second option can also be used to complete the well. With the casing still in the borehole, a wellpoint with a packer at the top can be lowered to the bottom of the casing. The casing is then pulled back to expose the screen. The original casing remains in the borehole to complete the well. Either of these completion techniques permit the installation of thermoplastic or fluoropolymer in addition to steel as the screen material.

A more complete listing of the applications and limitations of driven wells is found in Table 7.

Jet Percussion

In the jet-percussion drilling method, a wedge-shaped drill bit is attached to the lower end of the drill pipe (Figure 25). Water is pumped down the drill pipe under pressure and discharges through ports on each side of the drill bit. The bit is alternately raised and dropped to loosen unconsolidated materials or to break up rock at the bottom of the borehole. Concomitantly, the drill pipe is rotated by hand, at the surface, to cut a round and straight hole. The drilling fluid flows over the bit and up the annular space between the drill pipe and the borehole wall. The drilling fluid lubricates the bit, carries cuttings to the surface and deposits the cuttings in a settling pit. The fluid is then recirculated down the drill pipe.

In unconsolidated material the casing is advanced by a drive-block as the borehole is deepened. If the casing is positioned near the bottom of the borehole, good samples can be obtained as the cuttings are circulated to the surface and stratigraphic variations can be identified. Where the borehole is stable, the well can be drilled without simultaneously driving the casing.

After the casing has been advanced to the desired monitoring depth, a well intake can be installed by lowering through the casing. The casing is then pulled back to expose the well intake. Casing diameters of 4 inches or less can be installed by jet percussion. Depths of wells are typically less than 150 feet, although much greater depths have been attained. This method is most effective in drilling unconsolidated sands.

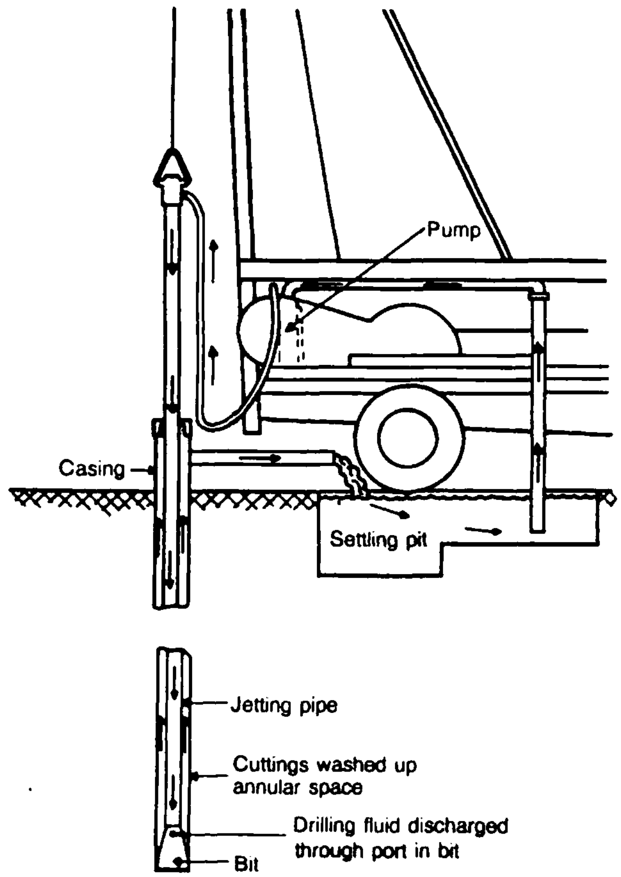

Figure 25. Diagram of jet-percussion drilling (after Speedstar Division of Koehring Company, 1983).

A more complete listing of applications and limitations of jet-percussion drilling is found in Table 8.

Solid-Flight Augers

Solid-flight augers (i.e. solid-stem, solid-core or continuous flight augers) are typically used in multiple sections to provide continuous flighting. The first, or lowermost, flight is provided with a cutter head that is approximately 2 inches larger in diameter than the flighting of the augers (Figure 26). As the cutting head is advanced into the earth, the cuttings are rotated upward to the surface by moving along the continuous flighting.

The augers are rotated by a rotary drive head at the surface and forced downward by a hydraulic pulldown or feed device. The individual flights are typically 5 feet in length and are connected by a variety of pin, box and keylock combinations and devices. Where used for monitoring well installation, available auger diameters typically range from 6 to 14 inches in outside diameter. Many of the drilling rigs used for monitoring well installation in stable unconsolidated material can reach depths of approximately 70 feet with 14-inch augers and approximately 150 feet with 6-inch augers.

In stable soils, cuttings can sometimes be collected at the surface as the material is rotated up the auger flights. The sample being rotated to the surface is often bypassed, however, by being pushed into the borehole wall of the shallower formations. The sample often falls back into the borehole along the annular opening and may not reach the surface until thoroughly mixed with other materials. There is commonly no return of samples to the surface after the first saturated zone has been encountered.

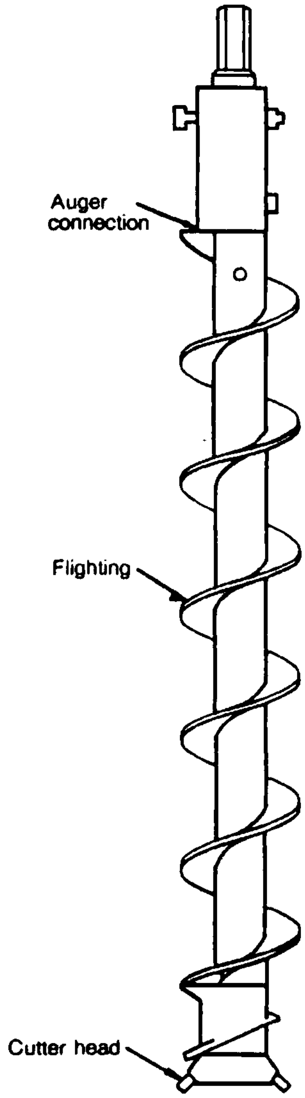

Figure 26. Diagram of a solid-flight auger (after Central Mine Equipment Company, 1987).

Samples may also be collected by carefully rotating the augers to the desired depth, stopping auger rotation and removing the augers from the borehole. In a relatively stable formation, samples will be retained on the auger flights as the augers are removed from the borehole. The inner material is typically more representative of the formation at the drilled depths and may be exposed by scraping the outer material away from the sample on the augers. Because the borehole often caves after the saturated zone is reached, samples collected below the water table are less reliable. The borehole must be redrilled every time the augers are removed, and the formation not yet drilled may be disturbed as the borehole above collapses. This is particularly true in heaving formations.

Table 6. Applications and Limitations of Hand Augers

Applications	Limitations
• Shallow soils investigations • Soil samples • Water-bearing zone identification • Piezometer, lysimeter and small diameter monitoring well installation • Labor intensive, therefore applicable when labor is inexpensive • No casing material restrictions	• Limited to very shallow depths • Unable to penetrate extremely dense or rocky soil • Borehole stability difficult to maintain • Labor intensive

Table 7. Applications and Limitations of Driven Wells

Applications	Limitations
• Water-level monitoring in shallow formations • Water samples can be collected • Dewatering • Water supply • Low cost encourages multiple sampling points	• Depth limited to approximately 50 feet (except in sandy material) • Small diameter casing • No soil samples • Steel casing interferes with some chemical analysis • Lack of stratigraphic detail creates uncertainty regarding screened zones and/or cross contamination • Cannot penetrate dense and/or some dry materials • No annular space for completion procedures

Table 8. Applications and Limitations of Jet-Percussion Drilling

Applications	Limitations
• Allows water-level measurement • Sample collection in form of cuttings to surface • Primary use in unconsolidated formations, but may be used in some softer consolidated rock • Best application is cinch borehole with 2-inch casing and screen installed, sealed and grouted	• Drilling mud may be needed to return cuttings to surface • Diameter limited to 4 inches • Installation slow in dense, bouldery clay/till or similar formations • Disturbance of the formation possible if borehole not cased immediately

Because the core of augers is solid steel, the only way to collect "undisturbed" split-spoon or thin-wall samples is to remove the entire string of augers from the borehole, insert the sampler on the end of the drill rod, and put the entire string back into the borehole. This sampling process becomes very tedious and expensive as the borehole gets deeper because the complete string of augers must be removed and reinserted each time a sample is taken. Sampling subsequent to auger removal is only possible if the walls of the borehole are sufficiently stable to prevent collapse during sampling. Boreholes are generally not stable after even a moderately thin saturated zone has been penetrated. This means that it is visually not possible to obtain either split-spoon or thin-wall samples after the shallowest water table is encountered.

The casing and well intake are also difficult to install after a saturated zone has been penetrated. In this situation, it is sometimes possible to auger to the top of a saturated zone, remove the solid augers and then install a monitoring well by either driving, jetting or bailing a well intake into position.

A more complete listing of the applications and limitations of solid-flight augers is found in Table 9.

Hollow-Stem Augers

Similar to solid-flight augers, hollow-stem auger drilling is accomplished using a series of interconnected auger flights with a cutting head at the lowermost end. As the augers are rotated and pressed downward, the cuttings are rotated up the continuous flighting.

Unlike the solid-flight augers the center core of the auger is open in the hollow-stem flights (Figure 27). Thus, as the augers are rotated and pressed into the ground, the augers act as casing and stabilize the borehole. Small-diameter drill rods and samplers can then be passed through the hollow center of the augers for sampling. The casing and well intake also can be installed without borehole collapse.

To collect the samples through hollow-stem augers, the augers are first rotated and pressed to the desired sampling depth. The inside of the hollow stem is cleaned out, if necessary. The material inside the auger can be removed by a spoon sampler with a retainer basket, jetting and/or drilling with a bit attached to smaller-diameter drill rods. If the jetting action is carried to the bottom of the augers, the material immediately below the augers will be disturbed. Next, either a split-spoon

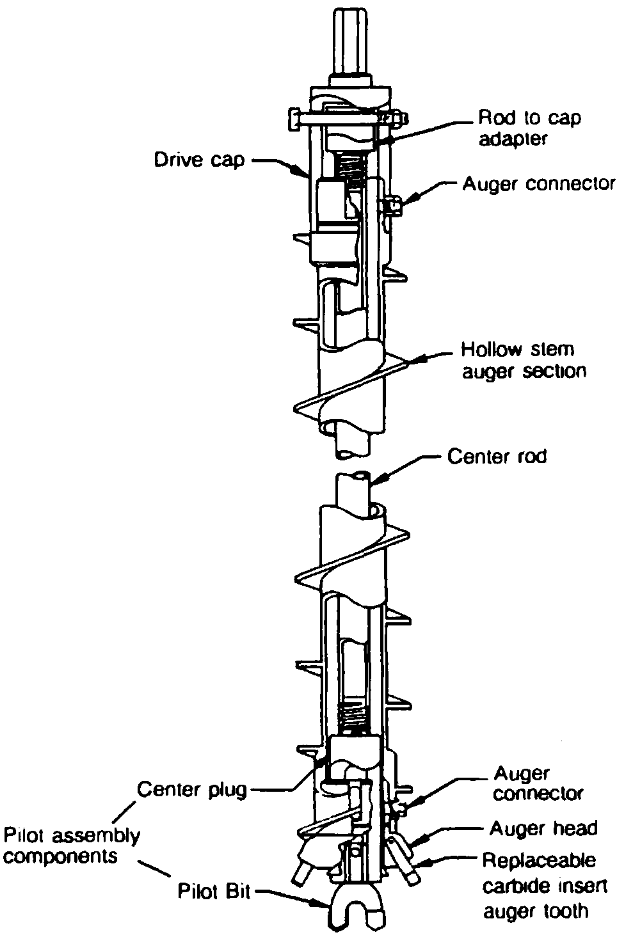

Figure 27. Typical components of a hollow-stem auger (after Central Mine Equipment Company, 1987).

(ASTM, 1586) or thin-wall (ASTM, 1587) sampler is placed on the lower end of the drill rods and lowered to the bottom of the borehole. The split-spoon sampler can then be driven to collect a disturbed sample or the thin-wall sampler can be pressed to collect an "undisturbed" sample from the strata immediately below the cutting head of the auger. Samples can either be taken continuously or at selected intervals. If sampling is continuous, the augers are rotated down to the bottom of the previously-sampled strata and cleaned out if necessary. The sampler is then reinserted through the auger and advanced into the undisturbed sediments ahead of the auger.

With the augers acting as casing and with access to the bottom of the borehole through the hollow stem, it is possible to drill below the top of the saturated zone. When the saturated zone is penetrated, finely-ground material and water may mix to form a mud that coats the borehole wall. This "mud plaster" may seal water-bearing zones and minimize inter-zonal cross connection. This sealing is uncontrolled and unpredictable because it depends on: 1) the quality of the silt/clay seal, 2) the differential hydrostatic pressure between the zones and 3) the transmissivity of the zones. Therefore, where possible cross contamination is a concern, the seal developed during augering cannot be relied upon to prevent cross contamination. One other potential source of cross contamination is through leakage into or out of the augers at the flighting joints. This leakage can be minimized by installing o-ring seals at the joints connecting the flights.

While drilling with hollow-stem augers with the center of the stem open, formation material can rise into the hollow stem as the auger is advanced. This material must be cleaned out of the auger before formation samples are collected. To prevent intrusion of material while drilling, hollow-stem auger boreholes can be drilled with a center plug that is installed on the bottom of the drill rods and inserted during drilling. A small drag bit may also be added to prevent intrusion into the hollow stem. An additional discussion on drilling with hollow-stem augers can be found in Appendix A, entitled, "Drilling and Constructing Monitoring Wells with Hollow-Stem Augers." Samples are collected by removing the drill rods and the attached center plug and inserting the sampler through the hollow stem. Samples can then be taken ahead of the augers.

When drilling into an aquifer that is under even low to moderate confining pressure, the sand and gravel of the aquifer frequently "heave" upward into the hollow stem. This heaving occurs because the pressure in the aquifer is greater than the atmospheric pressure in the borehole. If a center plug is used during drilling, heave frequently occurs as the rods are pulled back and the bottom of the borehole is opened. This problem is exacerbated by the surging action created as the center plug and drill rods are removed.

When heaving occurs, the bottom portion of the hollow stem fills with sediment, and the auger must be cleaned out before formation samples can be collected. However, the act of cleaning out the auger can result in further heaving, thus compounding the problem. Furthermore, as the sand and gravel heave upward into the hollow stem, the materials immediately below the auger are no longer naturally compacted or stratified. The sediments moving into the hollow stem are segregated by the upward-flowing water. It is obvious that once heaving has

Table 9. Applications and Limitations of Solid-Flight Augers

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

occurred, it is not possible to obtain a sample at that depth that is either representative or undisturbed.

Four common strategies that are used to alleviate heaving problems include:

1) adding water into the hollow stem in an attempt to maintain sufficient positive head inside the augers to offset the hydrostatic pressure of the formation;
2) adding drilling mud additives (weight and viscosity control) to the water inside the hollow stem to improve the ability of the fluid to counteract the hydrostatic pressure of the formation;
3) either screening the lower auger section or screening the lowermost portion of the drill rods both above and below the center plug, in such a manner that water is allowed to enter the auger. This arrangement equalizes the hydraulic pressure, but prevents the formation materials from entering the augers; and
4) drilling with a pilot bit, knock-out plug or winged clam to physically prevent the formation from entering the hollow stem.

The most common field procedure is to add water to the hollow stem. However, this method is frequently unsuccessful because it is difficult to maintain enough water in the auger to equalize the formation pressure as the drill rods are raised during the sampling process. Adding drilling mud may lessen the heaving problem, but volume replacement of mud displacement by removal of drilling rods must be fast enough to maintain a positive head on the formation. Additionally, drilling mud additives may not be desirable where questions about water-quality sampling from the monitoring well will arise. A third option, screening the lowermost auger flight, serves two purposes: 1) the formation pressure can equalize with minimal formation disturbance and 2) water-quality samples and small-scale pumping tests can be performed on individual zones within the aquifer or on separate aquifers as the formations are encountered. Wire-wound screened augers were developed particularly for this purpose and are commercially available (Figure 28). By using a pilot bit, knock-out plug or winged clam, heaving is physically prevented until these devices are removed for sampling. In essence, the hollow stem functions as a solid stem auger. However, once these devices are dislodged during sampling, problems with heaving may still need to be overcome by using an alternative strategy.

Hollow-stem augers are typically limited to drilling in unconsolidated materials. However, if the cutting head of the auger is equipped with carbide-tipped cutting teeth, it is often possible to drill into the top of weathered bedrock a short distance. The augers can then be used as temporary surface casing to shut off water flow that commonly occurs at the soil/rock interface. The seal by the augers may not be complete; therefore, this practice is not recommended where cross contamination is a concern. The rock beneath the casing can then be drilled with a small-diameter roller bit or can be cored.

The most widely-available hollow-stem augers are 6.25-inch outside diameter auger flights with 3.25-inch inside diameter hollow stems. The equipment most frequently available to power the augers can reach depths of 150 to 175 feet in clayey/silty/sandy soils. Much greater depths have been attained, but greater depths cannot be predictably reached in most settings. A 12-inch outside diameter auger with a 6-inch inside diameter hollow stem is becoming increasingly available, but the depth limit for this size auger is usually 50 to 75 feet. Because of the availability and relative ease of formation sample collection, hollow-stem augering techniques are used for the installation of the overwhelming majority of monitoring wells in the United States.

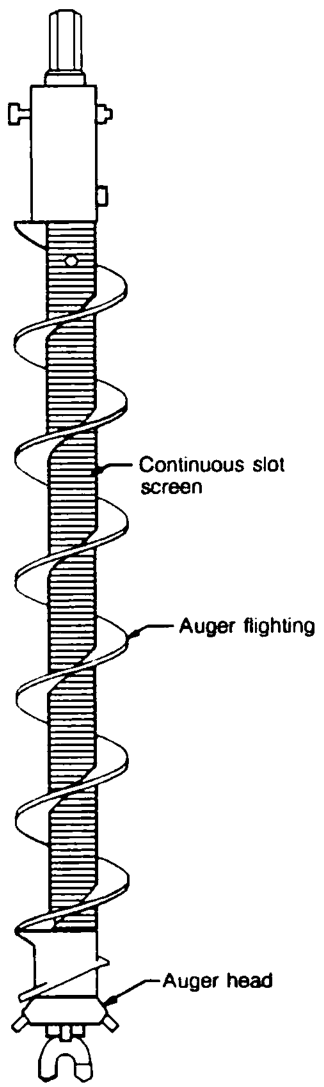

Figure 28. Diagram of a screened auger.

A more complete listing of the advantages and disadvantages of hollow-stem augers is found in Table 10. A more comprehensive evaluation of this technology is presented in Appendix A.

Direct Mud Rotary

In direct mud rotary drilling, the drilling fluid is pumped down the 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 wall

Table 10. Applications and Limitations of Hollow-Stem Augers

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

of the borehole. At the surface, the fluid discharges through a pipe or ditch and enters into a segregated or baffled sedimentation tank, pond or pit. The settling pit overflows into a suction pit where a pump recirculates the fluid back through the drill rods (Figure 29).

During drilling, the drill stem is rotated at the surface by either top head or rotary table drive. Down pressure is attained either by pull-down devices or drill collars. Pull-down devices transfer rig weight to the bit; drill collars add weight directly to the drill stem. When drill collars are used, the rig holds back the excess weight to control the weight on the bit. Most rigs that are used to install monitoring wells use the pull-down technique because the wells are relatively shallow.

Properly mixed drilling fluid serves several functions in mud rotary drilling. The mud: 1) cools and lubricates the bit, 2) stabilizes the borehole wall, 3) prevents the inflow of formation fluids and 4) minimizes cross contamination between aquifers. To perform these functions, the drilling fluid tends to infiltrate permeable zones and tends to interact chemically with the formation fluids. This is why the mud must be removed during the development process. This chemical interaction can interfere with the specific function of a monitoring well and prevent collection of a sample that is representative of the in-situ ground-water quality.

Samples can be obtained directly from the stream of circulated fluid by placing a sample-collecting device such as a shale shaker in the discharge flow before the settling pit. However, the quality of the samples obtained from the circulated fluid is generally not satisfactory to characterize the formations for the design of monitoring wells. Split-spoon, thin-wall or wireline samples can and should be collected when drilling with the direct rotary method.

Both split-spoon and thin-wall samples can be obtained in unconsolidated material by using a bit with an opening through which sampling tools can be inserted. Drilling fluid circulation must be broken to collect samples. The rotary drill stem acts as casing as the sample tools are inserted through the drillstem and bit and a sample is collected.

Direct rotary drilling is also an effective means of drilling and/or coring consolidated rock. Where overburden is present, an oversized borehole is drilled into rock and surface casing is installed and grouted in place. After the grout sets, drilling proceeds using a roller cone bit (Figure 30). Samples can be taken either from the circulated fluid or by a core barrel that is inserted into the borehole.

For the rig sizes that are most commonly used for monitoring well installation, the maximum diameter borehole is typically 12 inches. Unconsolidated deposits are sometimes drilled with drag or fishtail-type bits, and consolidated formations such as sandstone and shale are drilled with tricone bits. Where surface casing is installed, nominal 8-inch casing is typically used, and a 7 5/8 or 7 7/8-inch borehole is continued below the casing. In unconsolidated formations, these diameters permit a maximum 4-inch diameter monitoring well to be installed, filter-packed and sealed in the open borehole. In consolidated formations, a 4 5/8-inch outside diameter casing can be used in a 7 5/8-inch borehole because there are relatively few borehole wall stability problems in consolidated rock. This smaller annular space is usually sufficient to permit tremie placement of filter pack, bentonite seal and grout.

A more complete listing of applications and limitations of direct mud rotary drilling is found in Table 11.

Table 11. Applications and Limitations of Direct Mud Rotary Drilling

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

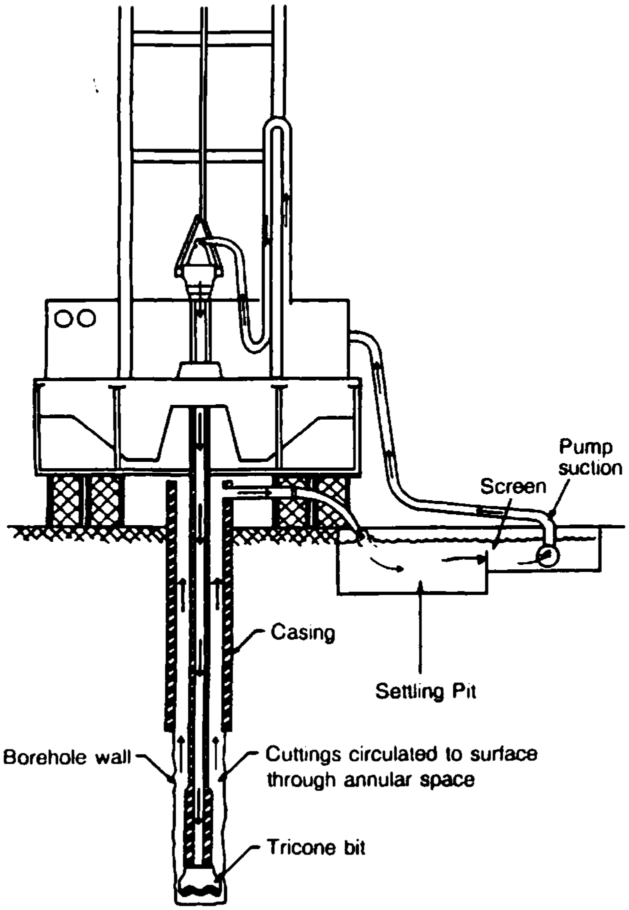

Figure 29. Diagram of a direct rotary circulation system (National Water Well Association of Australia, 1984).

Air Rotary Drilling

Air rotary drilling is very similar to direct mud rotary with the exception that the circulation medium is air instead of water or drilling mud. Air is compressed and circulated down through the drill rods and up the open hole. The rotary drill bit is attached to the lower end of the drill pipe, and the drill bit is advanced as in direct mud rotary drilling. As the bit cuts into the formation, cuttings are immediately removed from the bottom of the borehole and transported to the surface by the air that is circulating down through the drill pipe and up the annular space. The circulating air also cools the bit. When there is no water entering the borehole from the formation, penetration and sampling may be enhanced by adding small quantities of water and/or foaming surfactant. Foam very effectively removes the cuttings and lubricates and cools the bit. However, the drilling foam is not chemically inert and may react with the formation water. Even if the foam is removed during the development process, the representativeness of the ground-water quality sample may be questioned.

As the air discharges cuttings at the surface, formation samples can be collected. When the penetrated formation is dry, samples are typically very fine-grained. This "dust" is representative of the formation penetrated, but is difficult to evaluate in terms of the physical properties and characteristics of the formation. However, when small quantities of water are encountered during drilling or when water and surfactant are added to the borehole to assist in the drilling process, the size of the fragments that are discharged at the surface is much larger. These larger fragments provide excellent quality samples that are easier to interpret. Because the borehole is cleaned continuously and all of the cuttings are discharged, there is minimal opportunity for recirculation and there is minimal contamination of the cuttings by previously-drilled zones. Air discharged from a compressor commonly contains hydrocarbon-related contaminants. For this reason, it is necessary to install filters on the discharge of the compressor.

When drilling through relatively dry formations, thick water-bearing zones can easily be observed as drilling proceeds. However, thin water-bearing zones often are not identifiable because either the pressure of the air in the borehole exceeds the hydraulic pressure of the water-bearing zone or the combination and quantity of dust and air discharged is sufficient to remove the small amount of moisture indicative of the thin water-bearing zone. Where thin zones are anticipated, the samples must be carefully evaluated and drilling sometimes must be slowed to reduce absorption of the water by the dust. It may be desirable to frequently stop drilling to allow ground water to enter the open borehole. This technique applies only to the first water-bearing zones encountered, because shallower zones may contribute water to the open borehole. To prevent shallow zones from producing water or to prevent cross contamination, the shallower zones must be cased off. Identification of both thin and thick water-bearing zones is extremely important because this information assists greatly in the placement of well intakes and/or in the selection of isolated zones for packer tests.

In hard, abrasive, consolidated rock, a down-the-hole hammer can be substituted for a roller cone bit to achieve better penetration (Figure 31). With the down-the-hole drill, the compressed air that is used to cool the bit is also used to actuate and operate the down-the-hole hammer. Typical compressed air requirements range from 100 pounds per square inch to as much as 350 pounds per square inch for the latest generation of down-the-hole hammers. When a down-the-hole hammer is used, oil is required in the air stream to lubricate the hammer-actuating device. For this reason, down-the-hole hammers must be used with caution when constructing monitoring wells. Figure 32 shows the range of materials in which roller cone bits and down-the-hole pneumatic hammers operate most efficiently.

Air rotary drilling is typically limited to drilling in consolidated rock because of borehole instability problems. In air rotary drilling, no casing or drilling fluid is added to support the borehole walls, and the borehole is held open by stability of the rock and/or the air pressure used during drilling. In unconsolidated materials, there is the tendency for the borehole to collapse during drilling. Therefore, air rotary drilling in unconsolidated formations is unreliable and poses a risk for equipment. Where sufficient thicknesses of unconsolidated deposits overlie a consolidated formation that will be drilled by air rotary techniques, surface casing through the unconsolidated material is installed by an alternative technique. Drilling can then be accomplished using air with either a roller-cone bit or down-the-hole hammer.

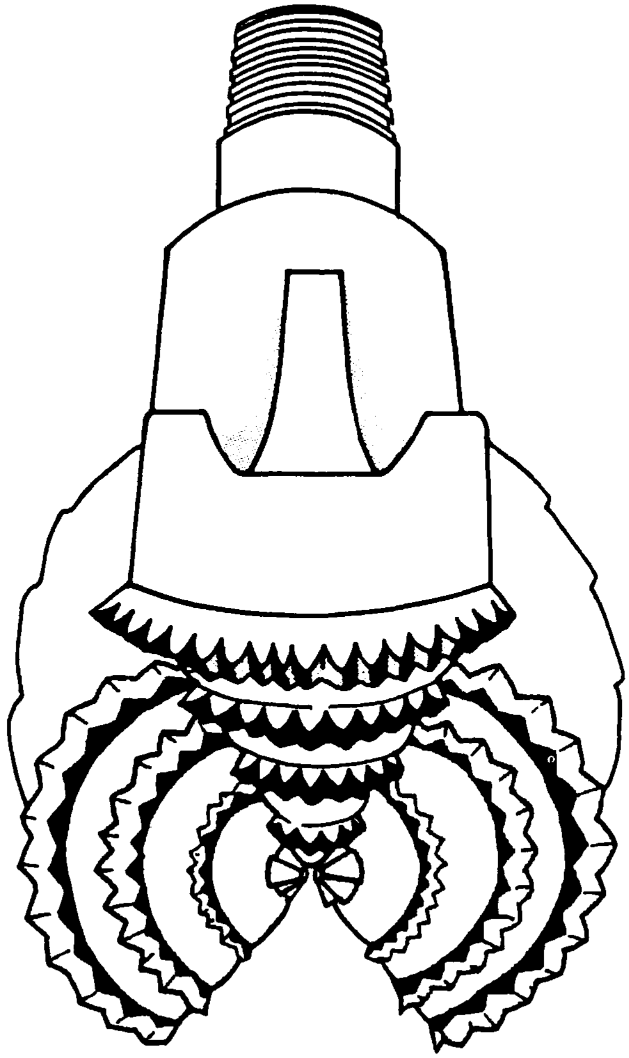

Figure 30. Diagram of a roller cone bit.

Monitoring wells drilled by air rotary methods are typically installed as open-hole completions. Because the borehole is uncased, the potential exists for cross connection between water-bearing zones within the borehole. Further, the recirculated air effectively cleans cuttings from the borehole walls so that the borehole is usually not coated with a wall cake such as occurs with mud rotary drilling or with augering techniques. This cleaner borehole wall increases the potential for cross connection, but increases the effectiveness of well completion and development. Additionally, the air introduced during drilling may strip volatile organics from the samples taken during drilling and from the ground water in the vicinity of the borehole. With time, the effects of airstripping will diminish and disappear, but the time necessary for this recovery will vary with the hydrogeologic conditions. The importance of these factors needs to be evaluated before choosing the air rotary drilling technique.

The diameter of the roller-cone or tri-cone bit used in air rotary drilling is limited to approximately 12 inches, although larger bits are available. For the down-the-hole hammer, the practical limitation is 8-inch nominal diameter. There is no significant depth limitation for monitoring well construction with the air rotary technique, with the possible exception of compressor capacity limits in deep holes with high water tables and back pressure.

A more complete list of applications and limitations of air rotary drilling is found in Table 12.

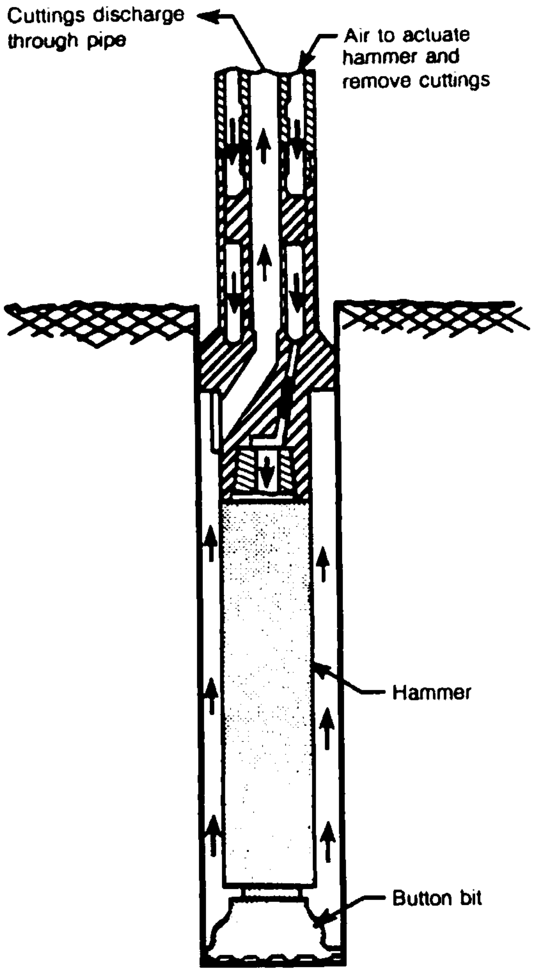

Figure 31. Diagram of a down-the-hole hammer (after Layne-Western Company, Inc., 1983).

Air Rotary With Casing Driver

This method is an adaptation of air rotary drilling that uses a casing-driving technique in concert with air (or mud) rotary drilling. The addition of the casing driver makes it possible to use air rotary drilling techniques in unconsolidated formations. The casing driver is installed in the mast of a top head drive air rotary drilling rig. The casing can then be driven as the drill bit is advanced (Figure 33).

The normal drilling procedure is to extend the drill bit 6 to 12 inches ahead of the casing. The distance that the drill bit can be extended beyond the casing is primarily a function of the stability of the borehole wall. It is also possible to drive the casing ahead of the bit. This procedure can be performed in unconsolidated formations where caving and an oversize borehole are of concern. Once the casing has been driven approximately one foot into the formation, the drill bit is used to clean the material from inside the casing. This technique also minimizes air or mud contact with the strata.

Where drilling through unconsolidated material and into consolidated bedrock, the unconsolidated formation is drilled with a drill bit as the casing is simultaneously advanced. When the casing has been driven into the top of the bedrock, drilling can proceed by the standard air rotary technique. The air rotary with casing driver combination is particularly efficient where drilling through the sand-gravel-silt-boulder-type materials that commonly occur in glaciated regions. The sandy and/or gravelly, unstable zones are supported by the casing while the boulder and till zones are rapidly penetrated by the rotary bit. Because the upper zones within the formation are cased-off as the borehole is advanced, the potential for inter-aquifer cross-contamination is minimized. The protective casing also permits the collection of reliable formation samples because the entire formation is cased except for the interval that is presently being cut. An additional advantage of the drill-through casing driver is that the same equipment can be used to drive the casing upward to expose the well intake after the casing and well intake have been installed in the borehole.

Water-bearing zones can be readily identified and water yields can be estimated as drilling progresses. However, as with the direct air rotary method, zones that have low hydrostatic pressure may be inhibited from entering the borehole by the air pressure exerted by the drilling process. Additionally, the dust created as the formation is pulverized can serve to seal off these zones and then these water-bearing zones may be overlooked. For these reasons, it is necessary to drill slowly and carefully and even occasionally to stop drilling where water-bearing zones are indicated or anticipated.

A more complete list of applications and limitations of the air rotary with casing driver method is found in Table 13.

Dual-Wall Reverse-Circulation

In dual-wall reverse-circulation rotary drilling, the circulating fluid is pumped down between the outer casing and the inner drill pipe, out through the drill bit and up the inside of the drill pipe (Figure 34).

Table 12. Applications and Limitations of Air Rotary Drilling

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

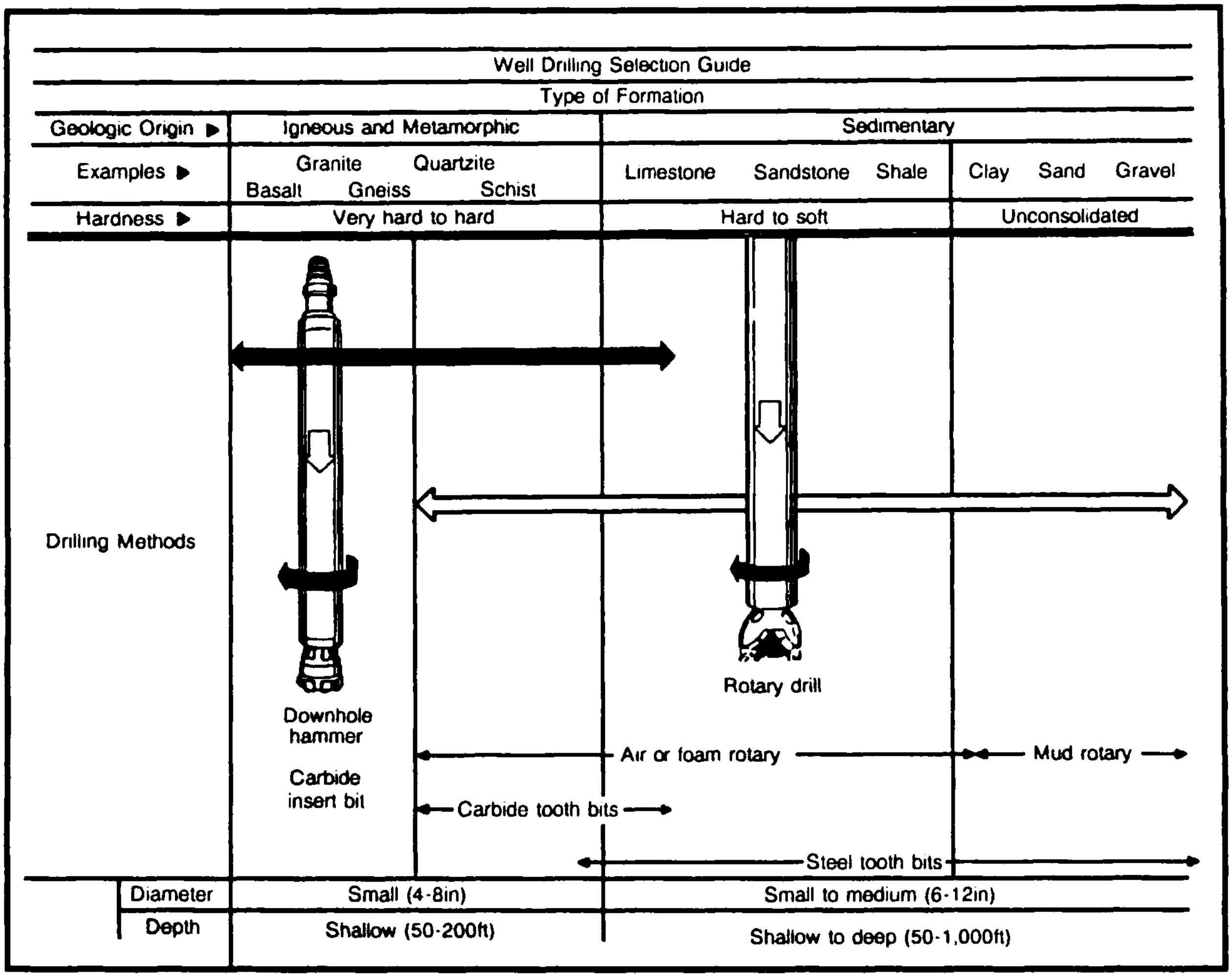

Figure 32. Range of applicability for various rotary drilling methods (Ingersoll-Rand, 1976).

The circulation fluid used in the dual-wall reverse circulation method can be either water or air. Air is the suggested medium for the installation of monitoring wells, and, as such, it is used in the development of the ratings in Appendix B. The inner pipe or drill pipe rotates the bit, and the outer pipe acts as casing. Similar to the air rotary with casing driver method, the outer pipe: 1) stabilizes the borehole, 2) minimizes cross contamination of cuttings and 3) minimizes interaquifer cross contamination within the borehole.

The dual-wall reverse-circulation rotary method is one of the better techniques available for obtaining representative and continuous formation samples while drilling. If the drill bit is of the roller-cone type, the formation that is being cut is located only a few inches ahead of the double-wall pipe. The formation cuttings observed at the surface represent no more than one foot of the formation at any point in time. The samples circulated to the surface are thus representative of a very short section of the formation. When drilling with air, a very representative sample of a thin zone can be obtained from the formation material and/or the formation water. Water samples can only be obtained where the formation has sufficient hydrostatic pressure to overcome the air pressure and dust dehydration/sealing effects. (Refer to the section on air rotary with casing driver for a more complete discussion.)

Unconsolidated formations can be penetrated quite readily with the dual-wall reverse-circulation method. Formations that contain boulders or coarse gravelly materials that are otherwise very difficult to drill can be relatively easily penetrated with this technique. This increased efficiency is due to the ability of the method to maximize the energy at the bottom of the borehole while the dual-wall system eliminates problems with lost circulation and/or borehole stability.

When drilling in hard rock a down-the-hole hammer can be used to replace the tri-cone bit. When the down-the-hole hammer is employed, air actuates the hammer by: 1) moving down through the hammer, 2) moving back up the outside of the hammer and 3) re-entering the center drill pipe in a cross-over

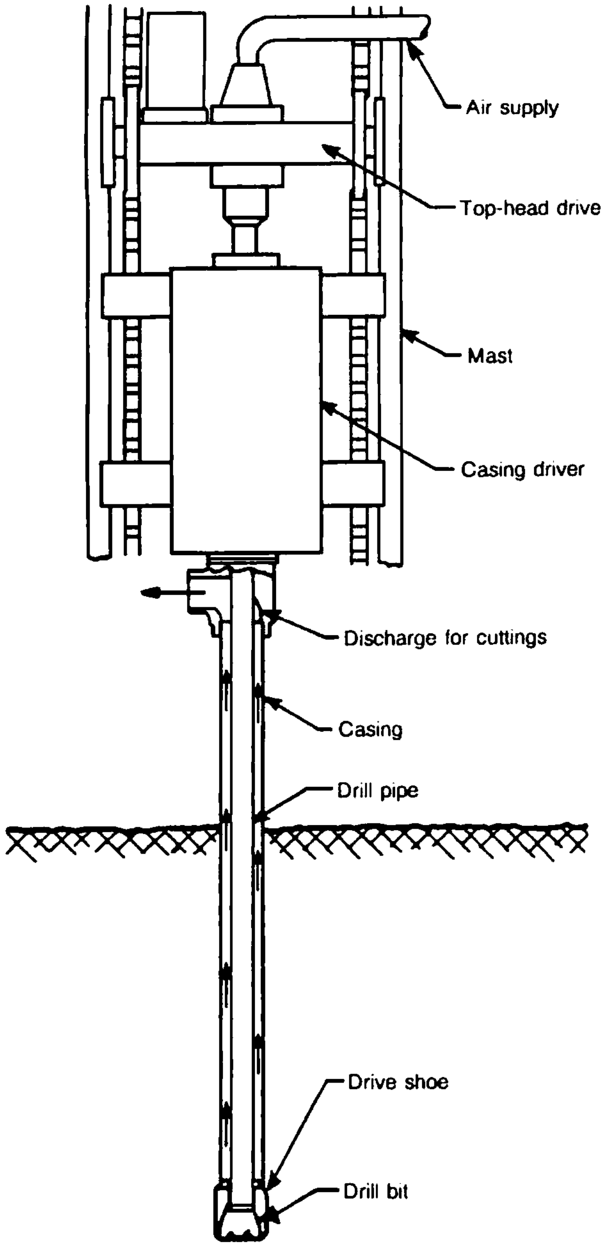

Figure 33. Diagram of a drill-through casing driver (Aardvark Corporation, 1977).

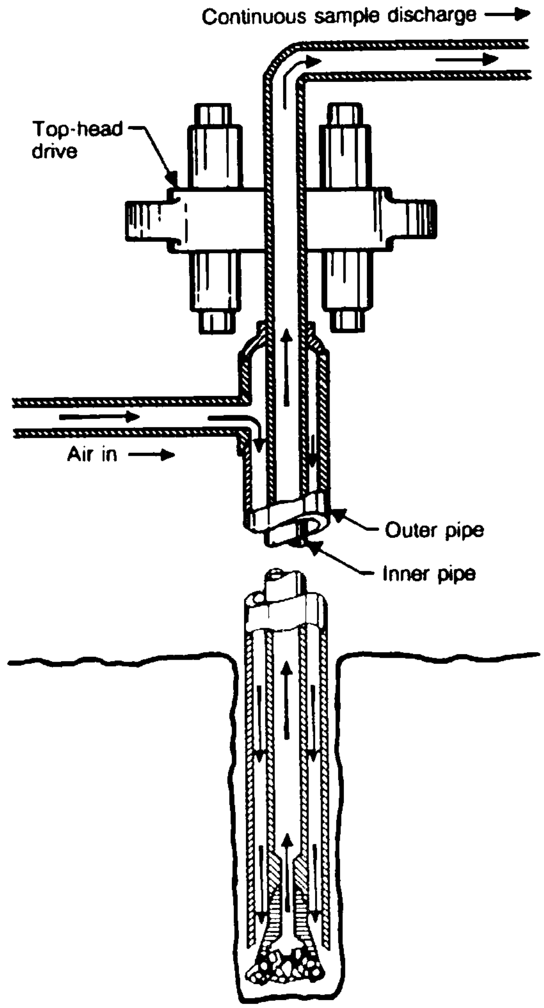

Figure 34. Diagram of dual-wall reverse-circulation rotary method (Driscoll, 1986).

channel just above the hammer. When drilling with the hammer, the full length of the hammer is exposed below the protective outer casing (approximately 4 to 5 feet). Thus the uncased portion of the borehole is somewhat longer than when drilling with a tri-cone bit. This longer uncased interval results in formation samples that are potentially representative of a thicker section of the formation. Otherwise, the sampling and representative quality of the cuttings are very similar to that of a formation drilled with a tri-cone bit. This method was developed for and has been used extensively by minerals exploration companies and has only recently been used for the installation of monitoring wells. Depths in excess of 1000 feet can be achieved in many formations.

When drilling with air, oil or other impurities in the air can be introduced into the formation. Therefore, when drilling with air and a roller-cone bit, an in-line filter must be used to remove oil or other impurities from the airstream. However, when using a down-the-hole hammer, oil is required in the airstream to lubricate the hammer. If oil or other air-introduced contaminants are of concern, the use of a down-the-hole hammer may not be advised.

When the borehole has been advanced to the desired monitoring depth, the monitoring well can be installed by either: 1) inserting a small diameter casing and well intake through an open-mouth bit (Driscoll, 1986) or 2) removing the outer casing prior to the installation of the monitoring well and installing the monitoring well in the open borehole. When installing a casing through the bit, the maximum diameter casing that can be installed is approximately 4 inches. This is controlled by the 10-inch maximum borehole size that is readily available with existing drill pipe and the maximum diameter opening in the bit. When installing a casing in the open borehole, the borehole must be very stable to permit the open-hole completion.

Table 13. Applications and Limitations of Air Rotary with Casing Driver Drilling

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

A more complete list of applications and limitations of the dual-wall reverse-circulation technique is found in Table 14.

Cable Tool Drilling

Cable tool drilling is the oldest of all the available modern drilling technologies. Prior to the development of direct mud rotary, it was the standard technology used for almost all forms of drilling.

In cable tool drilling, the drill bit is attached to the lower portion of the weighted drill stem that, in turn, is attached by means of a rope socket to the rope or cable (Figure 35). The cable and drill stem are suspended from the mast of the drill rig through a pulley. The cable runs through another pulley that is attached to an eccentric "walking or spudding beam." The walking beam is actuated by the engine of the drilling rig. As the walking beam moves up and down, the bit is alternately raised and dropped. This "spudding action" can successfully penetrate all types of geological formations.

When drilling in hard rock formations, the bit pounds a .ole into the rock by grinding cuttings from the formation. The cuttings are periodically excavated from the borehole by removing the drill bit and inserting a bailer (Figure 36). The bailer is a bucket made from sections of thin-wall pipe with a valve on the bottom that is actuated by the weight of the bailer. The bailer is run into the borehole on a separate line. The bailer will not function unless there is sufficient water in the borehole to slurry the mixture of cuttings in water. If enough water is present the bailer picks up the cuttings through the valve on the bottom of the bailer and is hoisted to the surface. The cuttings are discharged from either the top or bottom of the bailer, and a sample of the cuttings can be collected. If the cuttings are not removed from the borehole, the bit is constantly redrilling the same material, and the drilling effort becomes very inefficient.

When drilling unconsolidated deposits comprised primarily of silt and clay, the drilling action is very similar to that described in the previous paragraph. Water must be added to the borehole if the formations encountered during drilling do not produce a sufficient quantity of water to slurry the mud and silt. If the borehole is not stable, casing must be driven as the bit advances to maintain the wall of the borehole.

When drilling unconsolidated deposits comprised primarily of water-bearing sands and gravels, an alternate and more effective drilling technique is available for cable tool operations. In the "drive and bail" technique, casing is driven into the sand and gravel approximately 3 to 5 feet and the bailer is used to bail the cuttings from within the casing. These cuttings provide excellent formation samples because the casing serves, in effect, as a large thin-wall sampler. Although the sample is "disturbed," the sample is representative because the bailer has the capability of picking up all sizes of particles within the formation.

When drilling by the drive and bail technique, "heaving" of material from the bottom of the casing upward may present a problem. When heaving occurs, samples are not representative of the material penetrated by the casing. Instead, samples represent a mixture of materials from the zone immediately beneath the drill pipe. Heaving occurs when the hydrostatic pressure on the outside of the casing exceeds the pressure on the inside of the casing. The heaving is exacerbated by the action of the drill stem that is suspended in the borehole as the pipe is driven and by the action of the bailer that is used to take the samples. If the bailer is lifted or "spudded" rapidly, suction is developed that can pull the material from beneath the casing up into the casing. This problem is particularly prevalent when the drill advances from a dense material into relatively unconsolidated sand and gravel under greater hydrostatic pressure.

Several techniques have been developed to offset the problem of heaving. These techniques include:

1) maintaining the casing full of water as it is driven and as the well is bailed. The column of water in the casing creates a higher hydrostatic head within the casing than is present in the formation;
2) maintaining a "plug" inside the casing as the samples are taken with the bailer. This plug is created by collecting samples with the bailer

Table 14. Applications and Limitations of Dual-Wall Reverse-Circulation Rotary Drilling

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

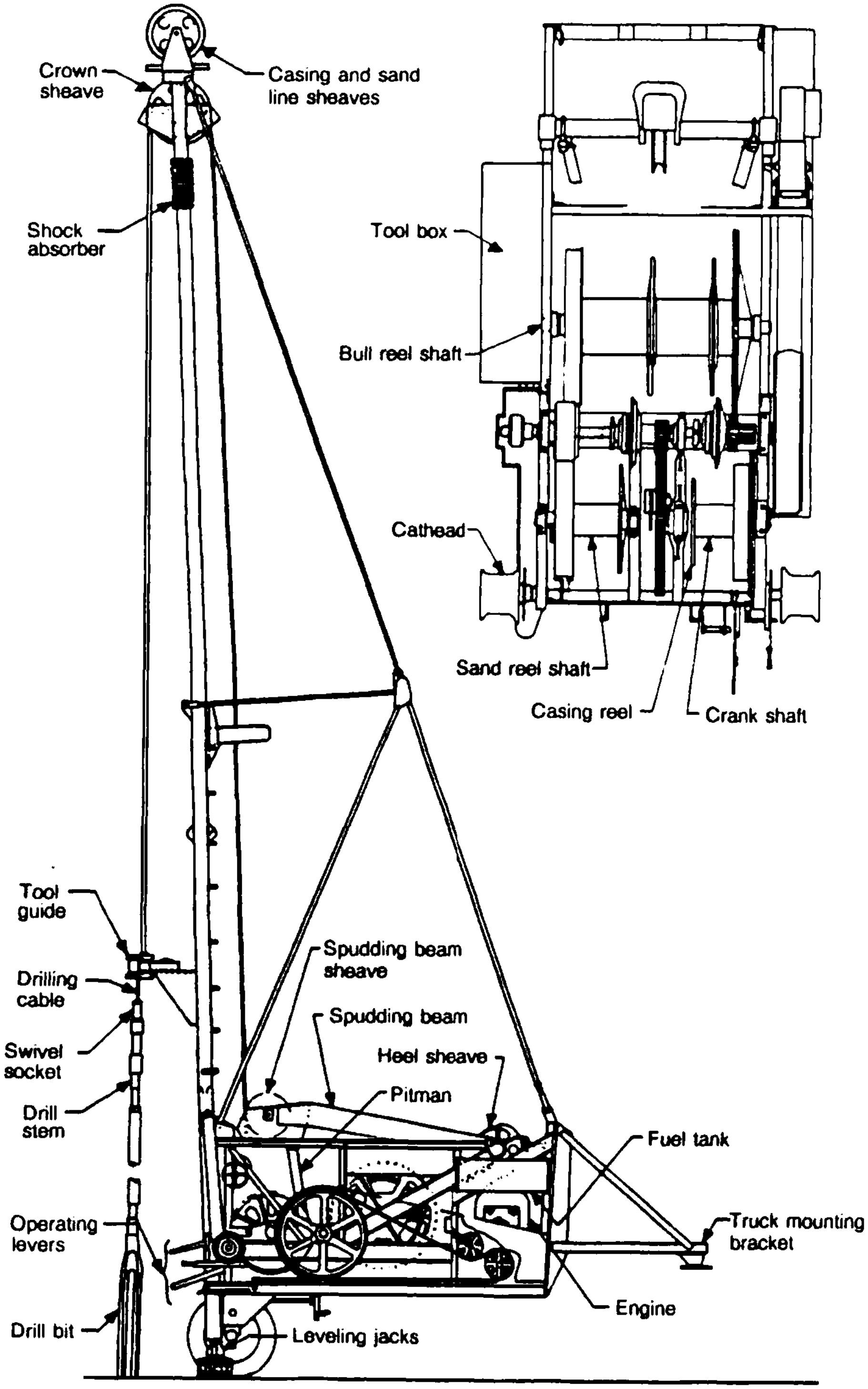

Figure 35. Diagram of a cable tool drilling system (Buckeye Drill Company/Bucyrus-Erie Company, 1982).

between 1 and 3 feet above the bottom of the casing. The plug maintained in the bottom of the "borehole" offsets heaving when the pressure differential is low;

3) overdriving the casing through the zone that has the tendency to heave; and
4) adding drilling mud to the borehole until the weight of the mud and slurried material in the casing exceed the hydrostatic pressure of the heaving zone. This fourth option is the least desirable because it adds drilling mud to the borehole.

If it is necessary to maintain a slurry in the casing in order to control heaving problems, it is still possible to collect both disturbed and undisturbed samples from beneath the casing by inserting smaller-diameter drill rods and samplers inside the casing at selected intervals.

Cable tool drilling has become less prevalent in the last 25 years because the rate of formation penetration is slower than with either rotary techniques in hard consolidated rock or augering techniques in unconsolidated formations. Because cable tool drilling is much slower, it is generally more expensive. Cable tool drilling is still important in monitoring well applications because of the versatility of the method. Cable tool rigs can be used to drill both the hardest and the softest formations. Cable tool rigs can drill boreholes with a diameter suitable to fulfill the needs of a monitoring well or monitoring well network. There is no significant depth limitation for the installation of monitoring wells.

When comparing cable tool to other drilling technologies, cable tool drilling may be the desired method. In a carefully drilled cable tool borehole, thin individual zones and changes in formations are often more easily identified than with alternative technologies. For example, smearing along sidewalls in unconsolidated formations is generally less severe and is thinner than with hollow-stem augering. Therefore, the prospect of a successful completion in a thin water-bearing zone is generally enhanced.

A more complete listing of advantages and disadvantages of cable tool drilling is found in Table 15.

Other Drilling Methods

There are two other drilling techniques that are commonly available to install monitoring wells: 1) bucket auger and 2) reverse circulation rotary. Bucket augers are primarily used for large-diameter borings associated with foundations and building structures. Reverse-circulation rotary is used primarily for the installation of large-diameter deep water wells.

While either of these technologies can be used for the installation of monitoring wells, the diameters of the boreholes and the size of the required equipment normally preclude them from practical monitoring well application. Unless an extraordinarily large diameter monitoring well is being installed, the size of the zone disturbed by the large diameter hole excavated by either of these techniques severely compromises the data acquisition process that is related to the sampling of the monitoring wells. While either of these techniques have possible application to monitoring well installation, they are not considered to be valid for regular application.

Drilling Fluids

Prior to the development of rotary drilling, water and natural clay were added to the borehole during cable tool drilling to: 1) cool and lubricate the bit, 2) slurry the cuttings for bailing and 3) generally assist in the drilling process. With the development of rotary drilling, the use of drilling fluid became increasingly important. In rotary drilling, the drilling fluid: 1) cools and lubricates the bit, 2) removes the cuttings and 3) simultaneously stabilizes the hole. Drilling fluid thus makes it possible to drill to much greater depths much more rapidly. As fluid rotary drilling programs became increasingly sophisticated, it became possible either to temporarily suspend cuttings in the mud column when the mud pump was not operating, or, under appropriate circumstances, to cause the cuttings to drop out in the mud pit when the cuttings reached the surface. These improvements served not only to enhance the efficiency of the drilling operation, but also to improve the reliability of the geologic information provided by the cuttings.

Today, the fluid system used in mud rotary drilling is no longer restricted to the use of water and locally-occurring natural clays. Systems are now available that employ a wide variety of chemical/oil/water-base and water-base fluids with a wide range of physical characteristics created by additives. The predominant additives include sodium bentonite and barium sulfates, but a variety of other chemicals are also used. This drilling fluid technology was initially developed to fulfill the deep-drilling requirements of the petroleum industry and is not generally applied to monitoring well installations.

Influence of Drilling Fluids on Monitoring Well Construction

Monitoring well construction is typically limited to the use of simple water-based drilling fluids. This limitation is imposed by the necessity not to influence the ground-water quality in the area of the well. Even when water-based fluids are used, many problems are still created or exacerbated by the use of drilling fluids. These problems include: 1) fluid infiltration/flushing of the intended monitoring zone, 2) well development difficulties (particularly where an artificial filter pack has been installed) and 3) chemical, biological and physical reactivity of the drilling fluid with the indigenous fluids in the ground.

As drilling fluid is circulated in the borehole during drilling operations, a certain amount of the drilling fluid escapes into the formations being penetrated. The escape, or infiltration into the formation, is particularly pronounced in more permeable zones. Because these more permeable zones are typically of primary interest in the monitoring effort, the most "damage" is inflicted on the zones of greatest concern. If the chemistry of the water in the formation is such that it reacts with the infiltrate, then subsequent samples taken from this zone will not accurately reflect the conditions that are intended to be monitored. Attempts to remove drilling fluids from the formation are made during the well development process. Water is typically removed in sufficient quantities to try to recover all the infiltrate that may have penetrated into the formation. When a sufficient quantity of water has been removed during development, the effects of flushing are arbitrarily considered to be minimized.

Table 15. Applications and Limitations of Cable Tool Drilling

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

Most monitoring wells are typically 2 to 4 inches in diameter. They are frequently surrounded by a filter pack to stabilize the formation and to permit the procurement of good ground-water samples. Because of the small well diameter, it is very difficult, and often not possible, to fully develop the drilling mud from the interface between the outside of the filter pack and the inside of the natural formation. Failure to fully remove this mudcake can interfere with the quality of the samples being obtained for a substantial period of time.

In practice, when ground-water sampling is undertaken, samples are usually collected and analyzed in the field for certain key parameters, including specific conductance, temperature and pH. Water is discharged from the well and repeated measurements are taken until the quality of the water being sampled has stabilized. When this "equilibrium" has been achieved and/or a certain number of casing volumes of water have been removed, the samples collected are commonly considered to be representative of the indigenous quality of the ground water. It is assumed that the drilling fluid filtrate no longer impacts the results of the sample quality. This is not necessarily the case. If, for example, the chemical reactions that took place between the drilling fluid and formation water(s) resulted in the precipitation of some constituents, then the indigenous water moving toward the well can redissolve some of the previously-precipitated constituents and give a false result to the sample. Theoretically, at some point in time this dissolution will be completed and the samples will become valid. However, there is currently no reliable method in practice that postulates the time frame required before reliable quality is attainable.

Biologic activity induced by the introduction of the drilling fluid may have a similar reaction. In particular, the use of organic drilling fluids, such as polymeric additives, has the potential for enhancing biologic activity. Polymeric additives include the natural organic colloids developed from the guar plant that are used for viscosity control during drilling. Biologic activity related to the decomposition of these compounds can cause a long-term variation in the quality of the water sampled from the well.

The use of sodium montmorillonite (bentonite) can also have a deleterious long-term impact on water quality. If the sodium-rich montmorillonite is not fully removed from the well during development, constituents contained in the ground water being monitored will come in contact with the montmorillonite. When this happens, the tendency is for both organic molecules with polar characteristics and inorganic cations to be attracted to positions within the sodium montmorillonite structure. This substitution results in the release of excess sodium ions and the retention of both selected organic molecules and cations. Organic molecules and cations that might otherwise be indicative of contamination can be removed from the sample and possibly be re-dissolved at an undefined rate into subsequent samples.

Drilling Fluid Characteristics

The principal properties of water-based drilling fluids are shown in Table 16. Selected properties are discussed in this section. Monitoring well construction typically starts by using only the simplest drilling fluid- -water; however, water should only be used when necessary. Any water added as a drilling fluid to a monitoring well should be the best quality of water that is available. The chemical and bacteriological quality of this water must be determined by laboratory analyses in order to identify potential interference with substances being monitored. As this "clean" water is circulated in the borehole, the water picks up clay and silt that form a natural drilling mud. During this process, both the weight and viscosity of the drilling fluid increase. The degree of change in these properties depends on the nature of the geologic formations being penetrated. It is possible to attain a maximum weight of approximately 11 pounds per gallon when drilling in natural clays. The same maximum weight can also be achieved by artificially adding natural clays or bentonite to make a heavier drilling mud where the formation does not naturally have these minerals.

Where additional weight is needed to maintain stability of the borehole, heavier additives are required. The most common material used for drilling mud weight control is barite (barium sulfate). Barite has an average specific gravity of approximately 4.25; the specific gravity of typical clay additives approximates 2.65. Figure 37 shows the range of drilling fluid densities that can be obtained by using a variety of different drilling additives.

When the weight of the drilling fluid substantially exceeds the natural hydrostatic pressure exerted by the formation being drilled, there is an excessive amount of water loss from the drilling fluid into the formation penetrated. This maximizes the filtrate invasion and consequently maximizes the adverse impact of filtrate invasion on the reliability of water-quality samples collected from the monitoring well.

Another important property of a drilling fluid is viscosity. Viscosity is the resistance offered by the drilling fluid to flow. In combination with the velocity of the circulated fluid, viscosity controls the ability of the fluid to remove cuttings from the borehole. In monitoring wells where water is the primary drilling fluid, the viscosity is the result of the interaction of water with the particulate matter that is drilled. Viscosity is also affected by the interaction of water with the clays that are sometimes added during the drilling process. Sodium montmorillonite (sodium bentonite) is the constituent most often added to increase viscosity.

Viscosity has no relationship to density. In the field, viscosity is measured by the time required for a known quantity of fluid to flow through an orifice of special dimensions. The instrument used for this measurement is called a Marsh Funnel. The relative viscosity of the drilling mud is described as the Marsh Funnel viscosity, in seconds. Table 17 presents the approximate Marsh Funnel viscosities required for drilling in typical unconsolidated materials. These typical values are based on the assumption that the circulating mud pump provides an adequate uphole velocity to clean the cuttings from the borehole at these viscosities. For comparison, the Marsh Funnel viscosity of clear water at 70°F is 26 seconds.

Table 16. Principal Properties of Water-Based Drilling Fluids (Driscoll, 1986)

Density (weight)	Gel strength
Viscosity	Fluid-loss-control effectiveness
Yield point	Lubricity (lubrication capacity)

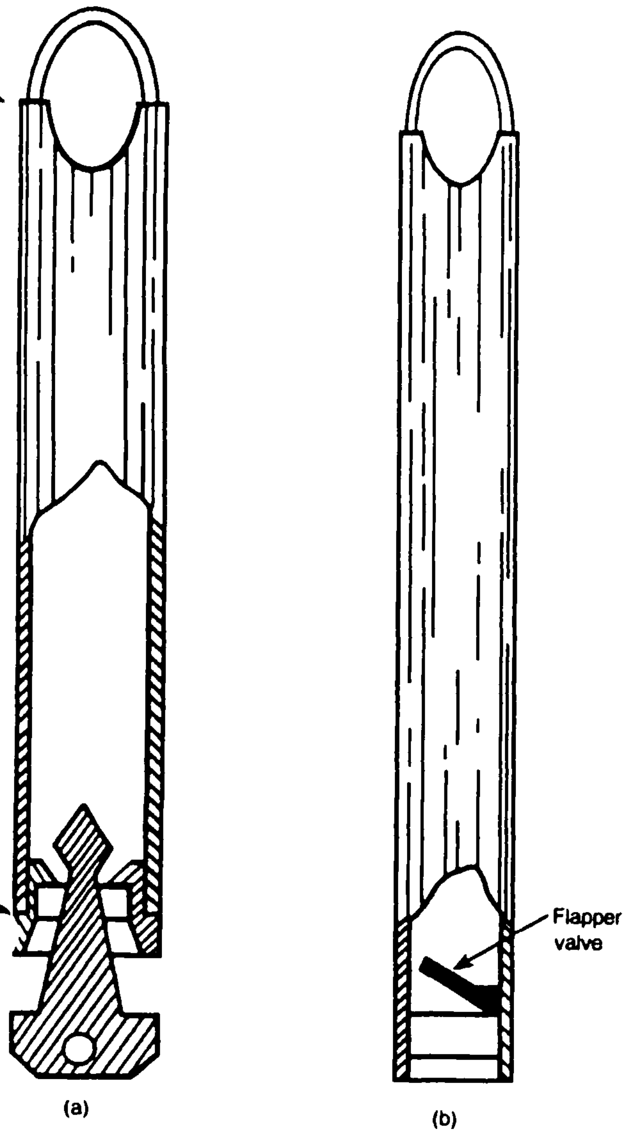

Figure 36. Diagrams of two types of bailers: a) dart valve and b) flat bottom.

Table 17. Approximate Marsh Funnel Viscosities Required for Drilling in Typical Types of Unconsolidated Materials (Driscoll, 1986)

Material Drilled	Appropriate Marsh Funnel Viscosity (seconds)
Fine sand	35 - 45
Medium sand	45 - 55
Coarse sand	55 - 65
Gravel	65 - 75
Coarse gravel	75 - 85

Clays are frequently a mixture of illite, chlorite, kaolinite and mixed-layer clays. These minerals all have a relatively low capability to expand when saturated. The reason that sodium montmorillonite is so effective in increasing viscosity is because of its crystalline layered structure; its bonding characteristics; and the ease of hydration of the sodium cation. Figure 38 demonstrates the variation in the viscosity building character-:s of a variety of clays. Wyoming bentonite (a natural .ium-rich montmorillonite) is shown at the extreme left.

The impact of the mix water on sodium bentonite is indicated by Figure 39. This figure shows the viscosity variation that results from using soft water versus hard water in drilling mud preparation. Sodium montmorillonite is most commonly used as the viscosity-building clay. However, in hard water the calcium and magnesium ions replace the sodium cation in the montmorillonite structure. As a consequence, a much lower viscosity is obtained for a given quantity of solids added. As previously discussed, this sodium cation replacement is similar to the activity that occurs in the subsurface when bentonitic materials are left in the proximity of the well. These materials have the capacity to prevent ions from reaching the borehole and to release them slowly back into the ground water at an indeterminate rate. This process can have a profound influence on the quality of the ground-water samples collected from the monitoring well.

The loss of fluid from the borehole into permeable zones during drilling occurs because the hydrostatic pressure in the borehole exceeds that of the formation being penetrated. As fluid moves from the borehole into the lower pressure zones, fine particulate matter that has been incorporated during the drilling operation, plus any clay additives that have been added to the drilling fluid, are deposited in the pore space of the zone being infiltrated. When this happens, a "filter cake" is formed on the borehole wall. Where a good quality bentonitic drilling mud additive is being used, this filter cake can be highly impermeable and quite tough. These characteristics minimize filtrate invasion into the formation, but make it difficult to develop these clays out of the zone penetrated.

Yield point and gel strength are two additional properties that are considered in evaluating the characteristics of drilling mud. Yield point is a measure of the amount of pressure, after a shut down, that must be exerted by the pump upon restarting, in order to cause the drilling fluid to start to flow. Gel strength is a measure of capability of the drilling fluid to maintain suspension of particulate matter in the mud column when the pump is shut down. There is a close relationship between viscosity, yield point and gel strength. In monitoring well installation these properties are rarely controlled because the control of these properties requires the addition of additives that can impact the quality of the water produced by the completed well. They are important, however, in evaluating the reliability of samples taken from the mud stream. Where drilling fluid quality is uncontrolled, ditch samples are generally unreliable.

Mud-Based Applications

It is desirable to install monitoring wells with the cleanest, clearest drilling water that is available. In monitoring well applications, the properties related to mud weight and the properties that relate to flow characteristics are only controlled under exceptional conditions. This control is usually exercised only on relatively deep boreholes or boreholes with moderately large diameters.

When drilling using either cable tool or hollow-stem augering techniques, it is sometimes necessary to add water to the borehole in order to effectively continue drilling. The addition of water may be required to: 1) stabilize the borehole, 2) improve the cutting action of the bit or 3) enable the driller to remove the cuttings from the borehole. With drive-and-bail and hollow-stem auger techniques, it may be necessary to add

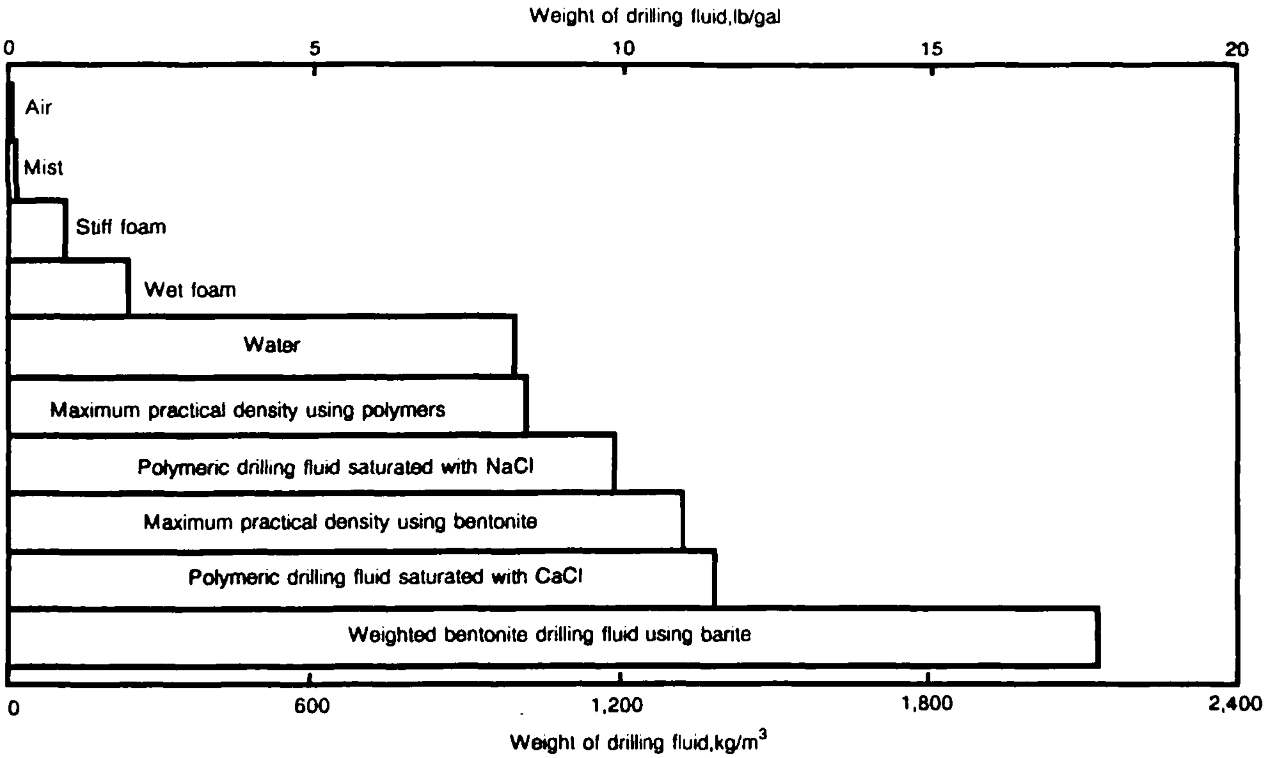

Figure 37. Practical drilling fluid densities (Driscoll, 1986).

water to the borehole to minimize heaving of the formation upward into the casing or hollow stem. When the zone immediately below the augers or the casing heaves, the samples collected from this zone are considered disturbed and are not representative of the natural undisturbed formation.

When drilling fluid is added during either cable tool drilling or hollow-stem augering, the effectiveness of the water is enhanced by the addition of bentonite to the drilling fluid. The bentonite is added to the borehole for formation stabilization. When either clean water or clean water plus additives are added to the borehole, the problems of flushing, potential contamination and water-quality modification are the same as when using fluid rotary drilling. For these reasons, it is suggested that addition of drilling fluid additives and/or even clean water be avoided when using cable tool or hollow-stem augers if at all possible. If it is anticipated that the addition of fluids will be necessary to drill with either cable tool or hollow-stem augers, it is suggested that alternative drilling techniques be considered.

Air-Based Applications

In addition to water-based drilling fluids, air-based drilling fluids are also used. There are a variety of air-based systems as indicated in Table 18. When using air-based drilling fluids, the same restrictions apply as when using water-based drilling fluids. When a monitoring well is drilled using additives other than dry air, flushing, potential contamination and water-quality modification are all of concern. Even with the use of dry air, there is the possibility that modification of the chemical environment surrounding the borehole may occur due to changes in the oxidation/reduction potential induced by aeration. This may cause stripping of volatile organics from formation samples and ground water in the vicinity of the borehole. With time, this effect will diminish and disappear, but the time necessary for this to occur varies with the hydrogeologic conditions.

Table 18. Drilling Fluid Options when Drilling with Air (after Driscoll, 1986)

- Air Alone
- Air Mist
  - Air plus a small amount of water/perhaps a small amount of surfactant
- Air Foam
  - Stable foam - air plus surfactant
  - Stiff foam - air, surfactant plus polymer or bentonite
- Aerated mud/water base - drilling fluid plus air

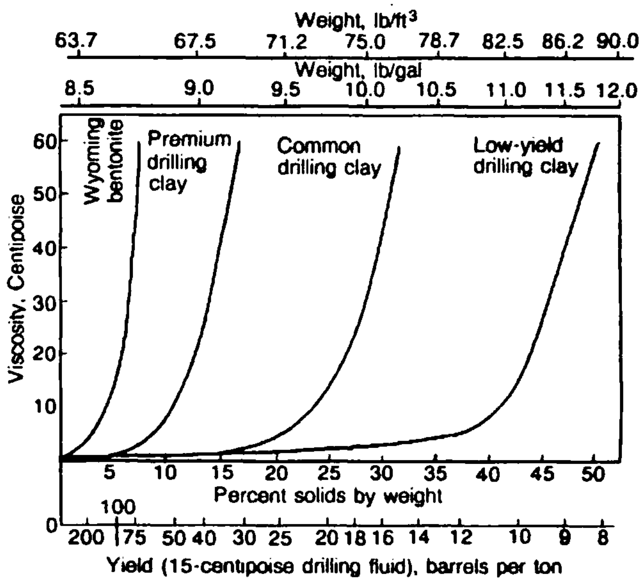

Figure 38. Viscosity-building characteristics of drilling clays (after Petroleum Extension Service, 1980).

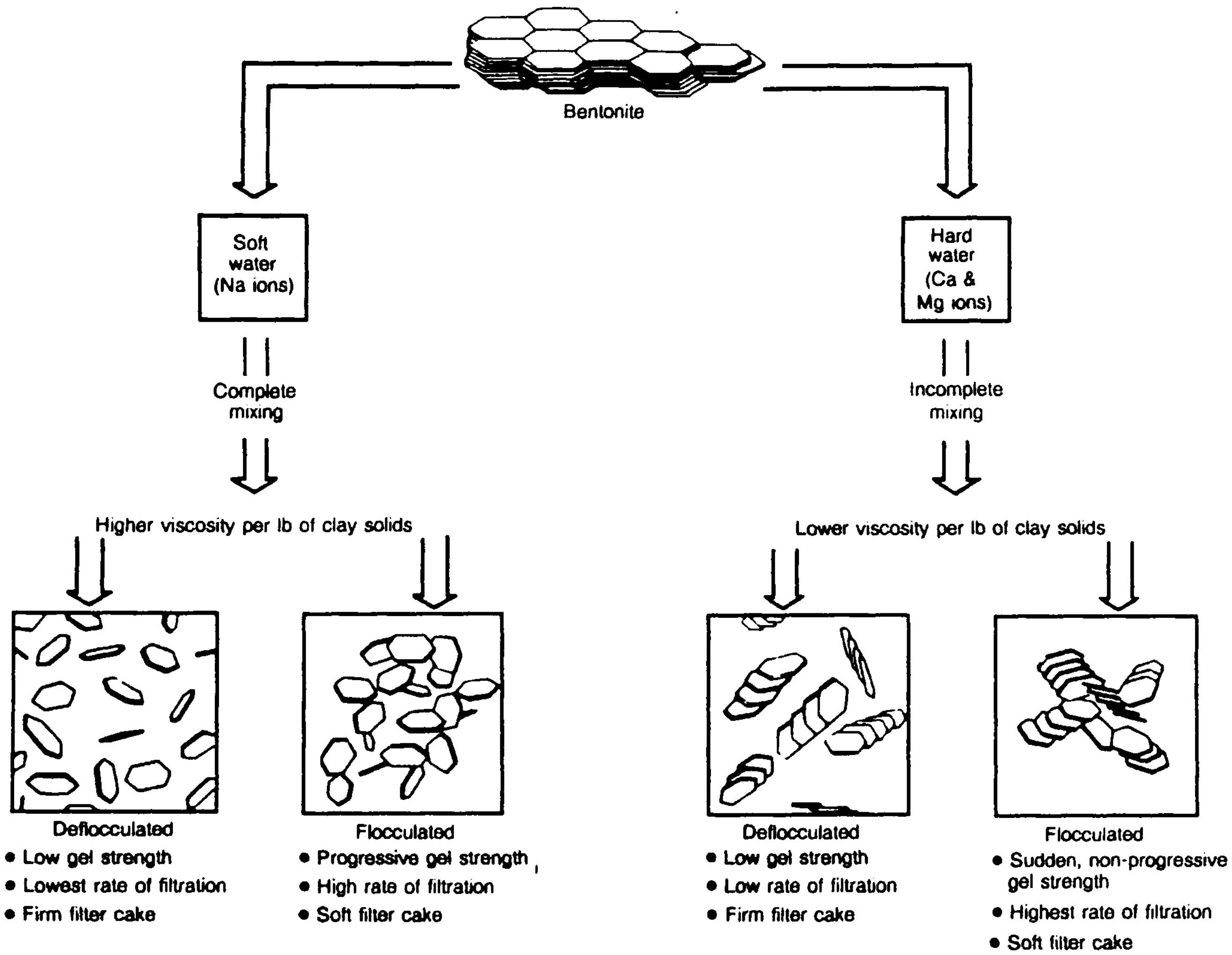

Figure 39. Schematic of the behavior of clay particles when mixed into water (Driscoll, 1986).

Where dry air is being used, a filter must be placed in the discharge line to remove lubricating oil. Because a down-the-hole hammer cannot be used without the presence of oil in the air stream, this particular variety of dry-air drilling cannot be used without the danger of contaminating the formation with lubricating oil.

Monitoring wells can be installed in hard rock formations using air as the circulation medium and employing roller-cone bits. Air can also be used successfully in unconsolidated formations when applied in conjunction with a casing hammer or a dual-wall casing technique. For effective drilling, the air supply must be sufficient to lift the cuttings from the bottom of the borehole, up through the annular space and to the discharge point at the surface. An uphole velocity of 5000 to 7000 feet per minute is desirable for deep boreholes drilled at high penetration rates.

Soil Sampling and Rock Coring Methods

It is axiomatic that: "any sample is better than no sample; and no sample is ever good enough." Thus, if there are no samples except those collected from the discharge of a direct rotary fluid drilled hole or those scraped from the cutting head or lead auger of a solid core auger, then these samples will be collected and analyzed to the best of the ability of the person supervising the operation. In general, however, it can be stated that in a monitoring well installation program these types of samples are not sufficient.

When evaluating the efficiency of a sampling program, the objectives must be kept in mind. Where formation boundaries must be identified in order to establish screened intervals, continuous samples are important. If identification of isolated zones with thin interfingers of sand and gravel in a clay matrix is important for the monitoring program, then the samples must allow identification of discrete zones within the interval being penetrated. If laboratory tests will be performed on the samples, then the samples must be of sufficient quality and quantity for laboratory testing. Specific laboratory tests require that samples be undisturbed; other tests permit the use of disturbed samples. The sample program must take these requirements into account.

Table 19 demonstrates the characteristics of the sampling methods available for the drilling techniques that are most

Table 19. Characteristics of Common Formation-Sampling Methods

Type of Formation	Sample Collection Method	Sample Quality	Potential for Continuous Sample Collection	Samples Suitable for Lab Tests	Discrete Zones Identifiable	Increasing Reliability
Unconsolidated						
	Solid core auger	Poor	No	No	No	
	Ditch (direct rotary)	Poor	Yes	No	No	
	Air rotary with casing driver	Fair	Yes	No	Yes	
	Dual-wall reverse circulation rotary	Good	Yes	No	Yes	
	Piston samplers	Good	No	Yes	Yes	
	Split spoon and thin-wall samplers	Good	Yes	Yes	Yes	
	Special samplers (Dennison, Vicksburg)	Good	Yes	Yes	Yes	
	Cores	Good	Yes	Yes	Yes	
Consolidated						
	Ditch (direct rotary)	Poor	Yes	No	No	
	Surface (dry air)	Poor	Yes	No	Yes	
	Surface (water/foam)	Fair	Yes	No	Yes	
	Cores (wireline or conventional)	Good	Yes	Yes	Yes	

frequently employed in the installation of monitoring wells. The table is arranged such that the general overall reliability of the samples increases downward in the table for both unconsolidated and consolidated materials. The least favorable type of sampling is the scraping of samples from the outside of the flights of solid-flight augers. This sampling method: 1) permits only discontinuous sampling, 2) does not allow identification of discrete zones, 3) provides no sample suitable for laboratory testing and 4) generally provides unreliable sample quality. It can also be seen from Table 19 that split-spoon and thin-wall sampling techniques are the minimum techniques required to obtain: 1) good sample quality, 2) continuous sampling, 3) samples suitable for laboratory testing and 4) samples that allow the identification of discrete zones.

Split-spoon sampling has become the standard for obtaining samples in unconsolidated materials by which other techniques are compared. Split-spoon samples are "driven" to collect disturbed samples; thin-wall samples are "pressed" to collect undisturbed samples. Undisturbed samples cannot be taken using driving, rotational or vibratory techniques in unconsolidated materials. Split-spoon and thin-wall sampling techniques are the primary techniques that are used to obtain data for monitoring well installation.

Sample description is as important as sample collection. It is often difficult to collect good formation samples of non-cohesive materials because the fine, non-cohesive particles are frequently lost during the sampling process. The person using and describing such sampling data must make an on-site, sample-by-sample determination of sample reliability if the data are to be used in a meaningful manner. Another sampling bias is that particulate material with an effective diameter greater than one-third of the inside diameter of the sampler frequently cannot be collected. It is not unusual for a single large gravel or small cobble to be caught at the bottom of the sampler and no sample at all recovered from a sampler run. It is also possible in a sequence of alternating saturated clay/silt and sand to "plug" the sampler with the clay/silt materials and to drive through the sands without any indication of sand. It is also common for the sample to be compacted so that if a 2-foot sampler is driven completely into the sediments, only 1.5 feet or less may actually be recovered.

It must be stressed that regardless of the sampling equipment used, the final results frequently depend on the subjective judgment of the person describing the samples. Therefore, in order to properly screen and develop a well in a potentially contaminated zone, it is often necessary to employ auxiliary techniques and substantial experience.

Split-Spoon Samplers

Split-spoon sampling techniques were developed to meet the requirements of foundation engineering. The common practice in foundation evaluation is to collect 18-inch samples at 5-foot intervals as the borehole is advanced. The split-spoon sampler is attached to the end of the drill rods and lowered to the bottom of the borehole where it rests on top of fresh undisturbed formation. In order to obtain valid samples, the bottom of the borehole must be clean and the formation to be sampled must be fresh and undisturbed. It is, therefore, easy to see why: 1) the difficulties of a heaving formation must be overcome prior to sampling and 2) a good sampling program can only be conducted in a stabilized borehole.

A split-spoon sampler, as shown in Figure 40, is of standard dimensions and is driven by a 140-pound weight dropped through a 30-inch interval. The procedure for collecting split-spoon samples and the standard dimensions for samplers are described in ASTM D1586 (American Society for Testing and Materials, 1984). The number of blows required to drive the split-spoon sampler provides an indication of the compaction/density of the soils being sampled. Because only 18-inch intervals are sampled out of every 5 feet penetrated, drilling characteristics (i.e. rate of penetration, vibrations, stability, etc.) of the formation being penetrated are also used to infer

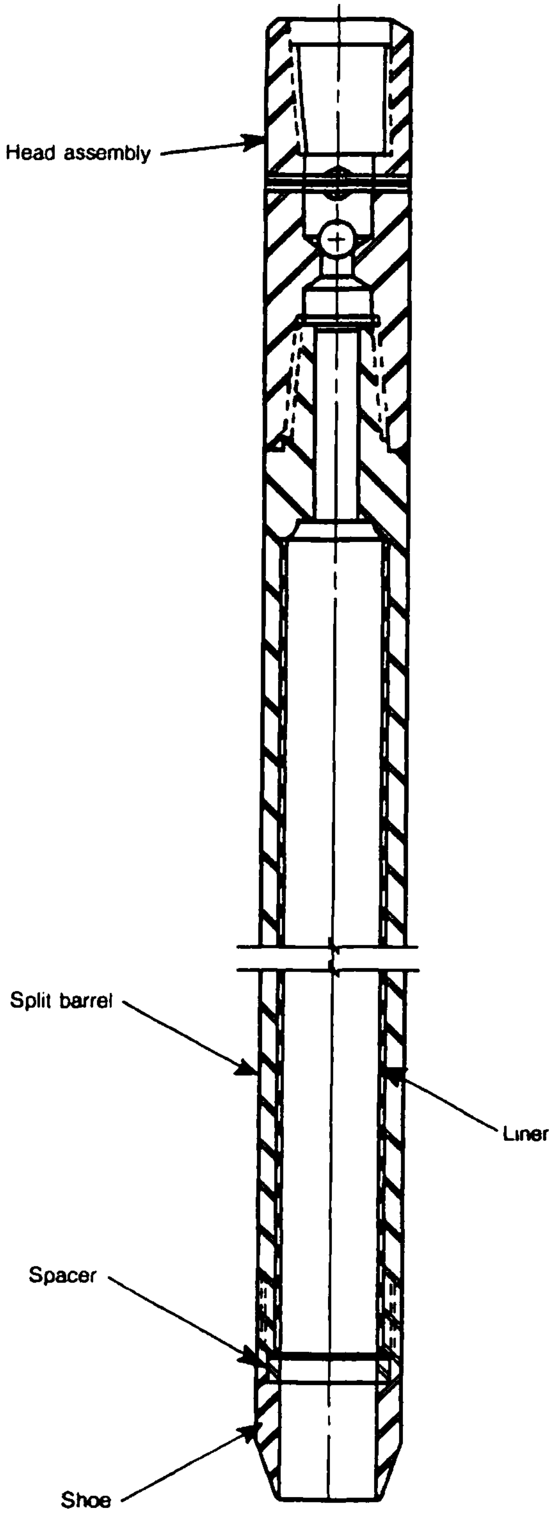

Figure 40. Diagram of a split-spoon sampler (Mobile Drilling Company, 1982).

characteristics of unsampled material. "Continuous" samples can also be taken with the split-spoon method by augering or drilling to the bottom of the previously-sampled interval and continuously repeating the operation. In order to obtain more accurate "N" values, a better approach is to attempt to collect two samples every five feet. This minimizes collection of samples in the disturbed zone in front of the bit. Continuous sampling is more time consuming, but is often the best way to obtain good stratigraphic data in unconsolidated sediments.

Table 20 shows the penetration characteristics of a variety of unconsolidated materials. The samples collected by split-spoon sampler are considered to be "disturbed" samples. They are, therefore, unsuitable for running certain laboratory tests, such as permeability.

Table 20. Standard Penetration Test Correlation Chart (After Acker, 1974)

Soil Type	Designation	Blows/Foot*
Sand and Silt	Loose	0-10
	Medium	11-30
	Dense	31-50
	Very Dense	>50
Clay	Very Soft	< 2
	Soft	3-5
	Medium	6-15
	Stiff	1-25
	Hard	>25

*Assumes: a) 2-inch outside diameter by 1 3/8-inch inside diameter sampler
b) 140-pound hammer falling through 30 inches

Thin-Wall Samplers

Work performed by Hvorslev (1949) and others have shown that if relatively undisturbed samples are to be obtained, it is imperative that the thickness of the wall of the sampling tube be less than 2.5 percent of the total outside diameter of the sampling tube. In addition, the ratio of the total area of the sampler outside diameter to the wall thickness area (area ratio) should be as small as possible. An area ratio of approximately 10 percent is the maximum acceptable ratio for thin-wall samplers; hence, the designation "thin-wall" samplers. Because the split-spoon sampler must be driven to collect samples, the wall thickness of the sampler must be structurally sufficient to withstand the driving forces. Therefore, the wall thickness of a split spoon sampler is too great for the collection of undisturbed samples.

The standard practice for collecting thin-wall samples, commonly referred to as Shelby tube samples, requires placing the thin-wall sampling tube at the end of the sampling drill rods. The sampler and rods are lowered to the bottom of the borehole just as is done with the split-spoon sampler. Instead of driving the sampler into the ground, the weight of the drill rig is placed on the sampler and it is pressed into place. This sampling procedure is described in detail in ASTM D1587 (American Society for Testing and Materials, 1983). A typical thin-wall sampler is shown in Figure 41.

The requirement that the area ratio be as small as possible presents a serious limitation on obtaining undisturbed samples in compact sediments. A thin-wall sampler may not have sufficient structural strength to penetrate these materials. A standard 2-inch inside diameter thin-wall sampler will frequently collapse without satisfactorily collecting a sample in soils with "N" values of 30 or greater. "N" values are a standard method of comparing relative density as derived from blow counts and are explained in ASTM D1586 (American Society for Testing and Materials, 1984).

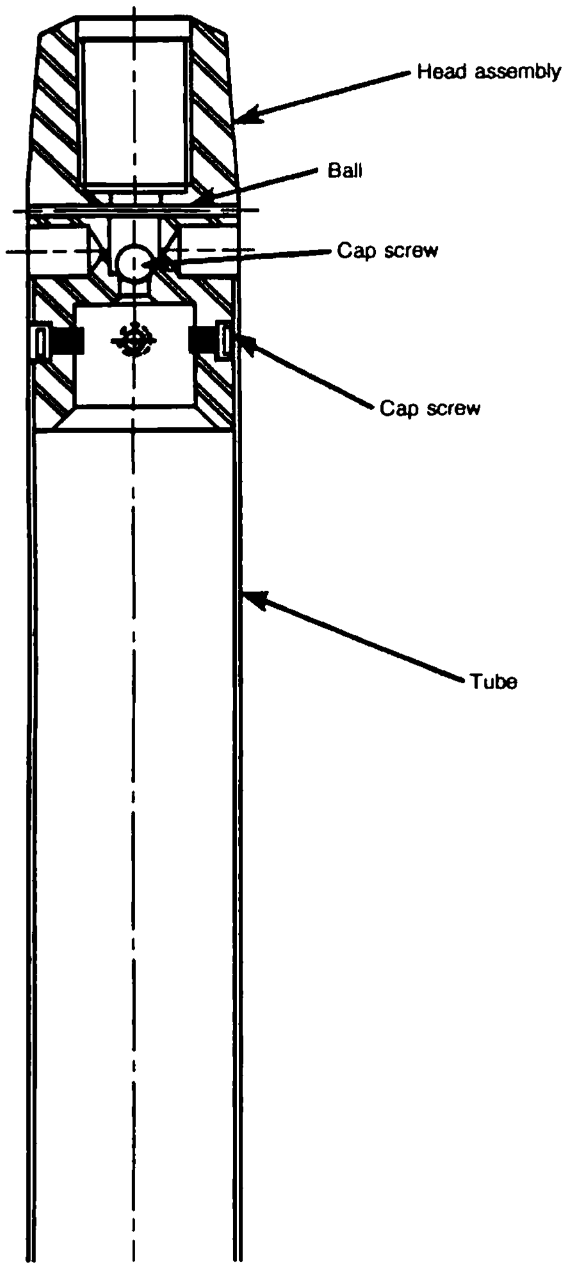

Figure 41. Diagram of a thin-wall sampler (Acker Drill Company, Inc., 1985).

Specialized Soil Samplers

Many special-function samplers have been developed to deal with special conditions. These include: 1) structurally strong thin-wall samplers that collect "undisturbed" samples, 2) large-diameter samplers that collect coarse sand and gravel for gradation analyses and 3) piston samplers that collect samples in heaving sands. Two good examples of the reinforced-type design are the Vicksburg sampler and the Dennison sampler, as shown in Figures 42a and 42b. Both samplers were developed by the United States Army Corps of Engineers and are so named for the districts in which they were first developed and used. The Vicksburg sampler is a 5.05-inch inside diameter by 5.25-inch outside diameter sampler that qualifies as a thin-wall sampler but is structurally much stronger than a Shelby tube. The Dennison sampler is a double-tube core design with a thin inner tube that qualifies as a thin-wall sampler. The outer tube permits penetration in extremely stiff deposits or highly cemented unconsolidated materials while the inner tube collects a thin-wall sample.

Examples of piston samplers are the internal sleeve piston sampler developed by Zapico et al. (1987) and the wireline piston sampler described by Leach et al. (1988) (Figures 43 and 44). Both samplers have been designed to be used with a hinged "clam-shell" device on the cutting head of a hollow-stem auger (Figure 45). The clam shell has been used in an attempt to: 1) improve upon a non-retrievable knock-out plug technique, 2) simplify sample retrieval and 3) increase the reliability of the sampling procedure in heaving sand situations. The Zapico et al. (1987) device requires the use of water or drilling mud for hydrostatic control while the Leach et al. (1988) device permits the collection of the sample without the introduction of any external fluid. The limitation of using this technique is that only one sample per borehole can be collected because the clam shell device will not close after the sampler is inserted through the opening. This means that although sample reliability is good, the cost per sample is high.

In both split-spoon and thin-wall sampling, it is common for a portion of the sample to be lost during the sampling process. One of the items to be noted in the sample description is the percent recovery, or the number of inches that are actually recovered of the total length that was driven or pressed. To help retain fine sand and gravel and to prevent the sample from being lost back into the borehole as the sample is removed, a "basket" or a "retainer" is placed inside the split-spoon sampler. Figure 46 shows the configuration of four commercially-available types of sample retainers. A check valve is also usually installed above the sampler to relieve hydrostatic pressing during sample collection and to prevent backflow and consequent washing during withdrawal of the sampler.

Except for loss of sample during collection, it is possible to collect continuous samples with conventional split-spoon or thin-wall techniques. These involve: 1) collecting a sample, 2) removing the sampler from the borehole, 3) drilling the sampled interval, 4) reinserting the sampler and 5) repeating the process. This effort is time consuming and relatively expensive, and it becomes increasingly expensive in lost time to remove and reinsert the sampler and rods as the depths exceed 100 feet.

To overcome this repeated effort, continuous samplers have been developed. One such system is shown in Figure 47. A continuous sample is taken by attaching a 5-foot long thin-wall tube in advance of the cutting head of the hollow-stem auger. The tube is held in place by a specially designed latching mechanism that permits the sample to be retracted by wire line when full and replaced with a new tube. A ball-bearing fitting in the latching mechanism permits the auger flights to be rotated without rotation of the sampling tube. Therefore, the sampling tube is forced downward into the ground as the augers are rotated.

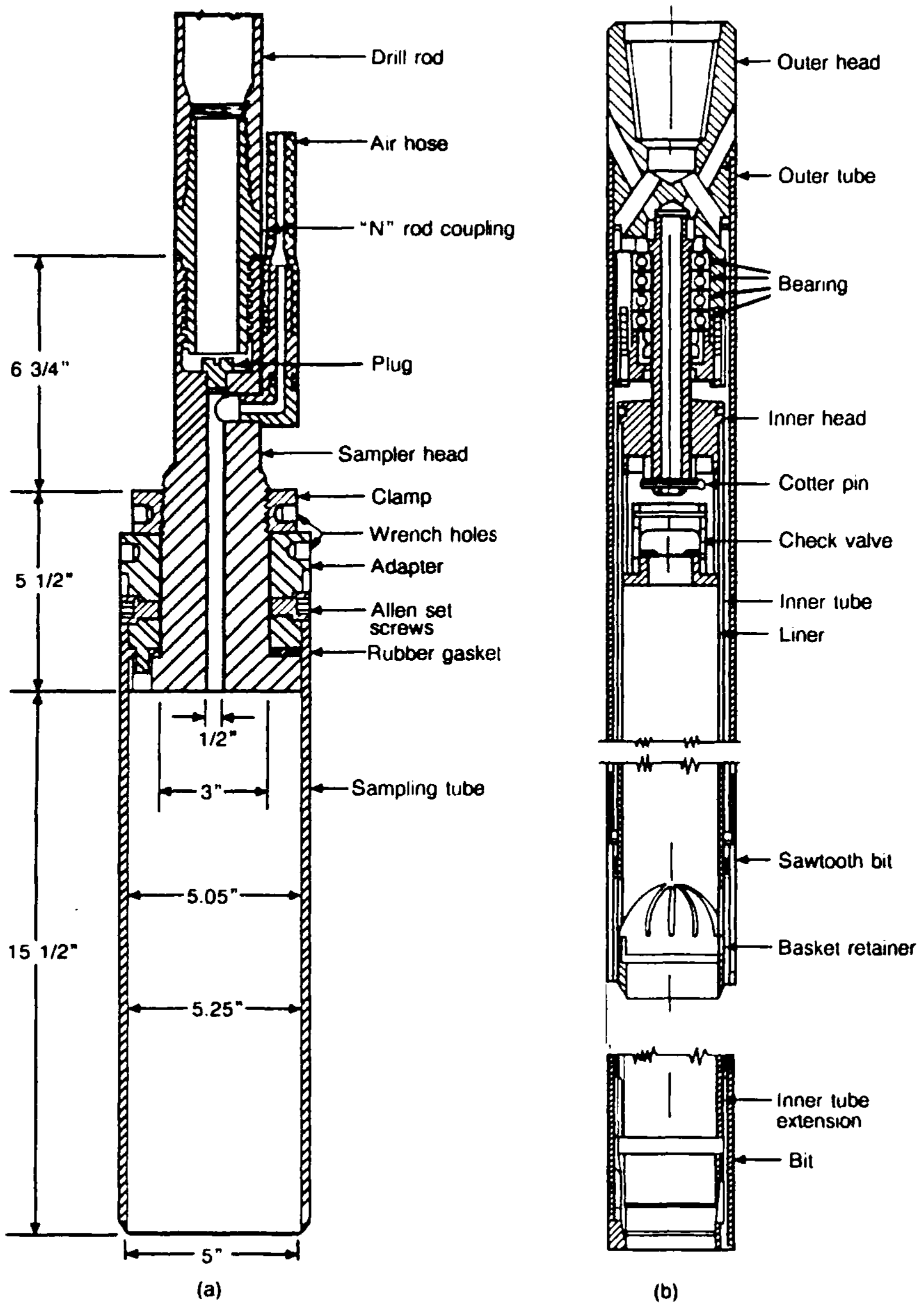

Figure 42. Two types of special soil samplers: a) Vicksburg sampler (Krynine and Judd, 1957) and b) Dennison sampler (Acker Drill Company, Inc., 1985).

Core Barrels

When installing monitoring wells in consolidated formations the reliability and overall sample quality of the drilled samples from either direct fluid rotary or air, water and foam systems is very similar to that of the samples obtained in unconsolidated formations. Where reliable samples are needed to fully characterize the monitored zone, it is suggested that cores be taken. Coring can be conducted by either wireline or ·nventional methods. Both single and double-tube core bar-ɹls are available as illustrated in Figures 48a and 48b.

In coring, the carbide or diamond-tipped bit is attached to the lower end of the core barrel. As the bit cuts deeper, the formation sample moves up the inside of the core tube. In the single-wall tube, drilling fluid circulates downward around the core that has been cut, flows between the core and the core barrel and exits through the bit. The drilling fluid then circulates up the annular space and is discharged at the land surface. Because the drilling fluid is directly in contact with the core, poorly-cemented or soft material is frequently eroded and the core may be partially or totally destroyed. This problem exists where formations are friable, erodable, soluble or highly frac-

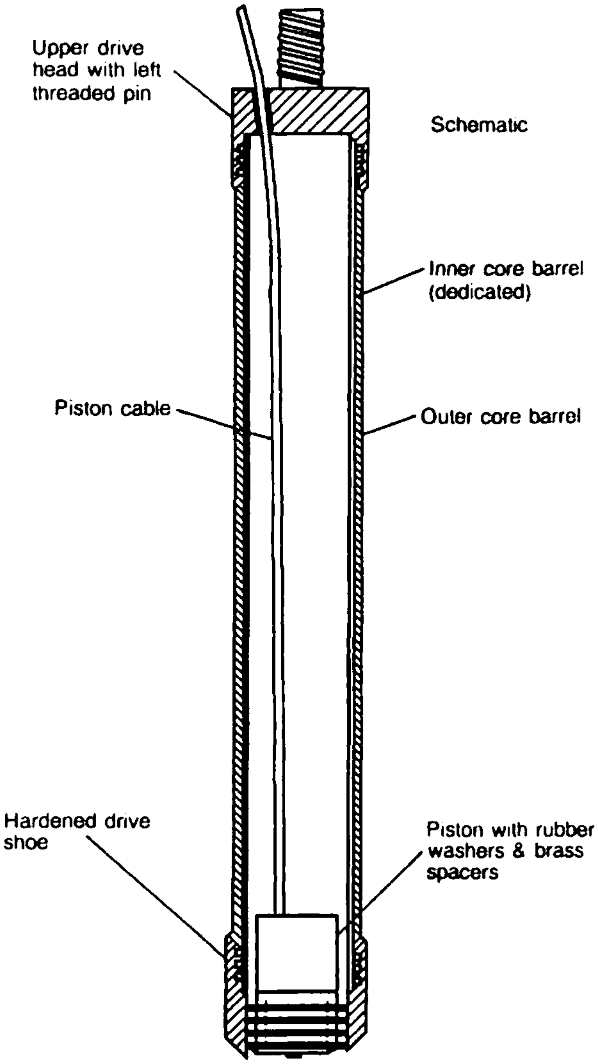

Figure 43. Internal sleeve wireline piston sampler (Zapico et al., 1987).

tured. In these formations very little or no core may be recovered.

In these circumstances a double-wall core barrel may be necessary. In a double-wall core barrel, the drilling fluid is circulated between the two walls of the core barrel and does not directly contact the core that has been cut. As drilling fluid circulates between the two walls of the core barrel, the core moves up into the inner tube, where it is protected. As a result, better cores of poorly-consolidated formations can be recovered. Good recovery can be obtained even in unconsolidated clays and silts using a double-wall coring technique.

Selection of Drilling Methods for Monitoring Well Installation

Matrix Purpose

The most appropriate drilling technology for use at a specific site can only be determined by evaluating both the hydrogeologic setting and the objectives of the monitoring program. To assist the user in choosing an appropriate drilling technology, a set of matrices has been developed that lists the most commonly used drilling techniques for monitoring well installation and delineates the principal criteria for evaluating those drilling methods. A matrix has been developed for a unique set of hydrogeologic conditions and well design requirements that limit the applicability of the drilling techniques. Each applicable drilling method that can be used in the described hydrogeologic setting and with the stated specific design requirements has been evaluated on a scale of 1 to 10 with respect to the criteria listed in the matrix. A total number for each drilling method was computed by adding the scores for the various criteria. The totals represent a relative indication of the desirability of the drilling methods for the specified conditions.

Matrix Description and Development

A set of 40 matrices has been developed to depict the most prevalent general hydrogeologic conditions and well design requirements for monitoring wells. The complete set of matrices are included as Appendix B. The matrices were developed from a combination of five factors including:

1) unconsolidated or consolidated geologic formations encountered during drilling,
2) saturated or unsaturated conditions encountered during drilling,
3) whether or not invasion of the monitored zone by drilling fluid is permitted,
4) depth range of the monitoring well: 0 to 15 feet, 15 to 150 feet or greater than 150 feet and
5) casing diameter of the monitoring well: less than 2 inches, 2 to 4 inches or 4 to 8 inches.

Table 21 indicates the number of the matrix that corresponds to the combination of factors used to develop the numbers on each matrix.

Each matrix provides a relative evaluation of the applicability of selected drilling methods commonly used to construct monitoring wells. The drilling methods evaluated in the matrix include:

1) hand auger,
2) driving,
3) jet percussion,
4) solid flight auger,
5) hollow stem auger,
6) mud rotary,
7) air rotary,
8) air rotary with casing driver,
9) dual-wall rotary and
10) cable tool.

A complete description of these drilling techniques and their applicability to monitoring well installations can be found in the beginning of this chapter under the heading entitled "Drilling Methods for Monitoring Well Installation."

The drilling techniques have been evaluated with respect to a set of criteria that also influences the choice of a drilling method. These additional criteria include:

1) versatility of the drilling method,
2) sample reliability,

Table 21. Index to Matrices 1 through 40

Matrix Number \ General Hydrogeologic Conditions and Well Design Requirements	Unconsolidated	Consolidated	Saturated	Unsaturated	Invasion Permitted	Invasion Prohibited	Depth 0-15 Feet	Depth 15-150 Feet	Depth > 150 Feet	<2-Inch Diameter Casing	2-4 Inch Diameter Casing	4-8 Inch Diameter Casing
1	X		X		X		X			X		
2	X		X		X			X		X		
3	X		X		X				X	X		
4	X		X		X		X				X	
5	X		X		X			X			X	
6	X		X		X				X		X	
7	X		X		X		X					X
8	X		X		X			X				X
9	X		X		X				X			X
10	X		X			X	X			X		
11	X		X			X		X		X		
12	X		X			X			X	X		
13	X		X			X	X				X	
14	X		X			X		X			X	
15	X		X			X			X		X	
16	X		X			X	X					X
17	X		X			X		X				X
18	X		X			X			X			X
19	X			X	X		X			X		
20	X			X	X			X		X		
21	X			X	X				X	X		
22	X			X	X		X				X	
23	X			X	X			X			X	
24	X			X	X						X	
25	X			X	X				X			X
26	X			X	X		X					X
27	X			X	X			X				X
28	X			X		X			X	X		
29	X			X		X	X			X		
30	X			X		X		X		X		
31	X			X		X			X		X	
32	X			X		X	X				X	
33	X			X		X		X			X	
34	X			X		X			X			X
35	X			X		X	X					X
36	X			X	X	X		X				X
37		X			X				X		X	
38		X										X
39		X				X					X	
40		X				X						X

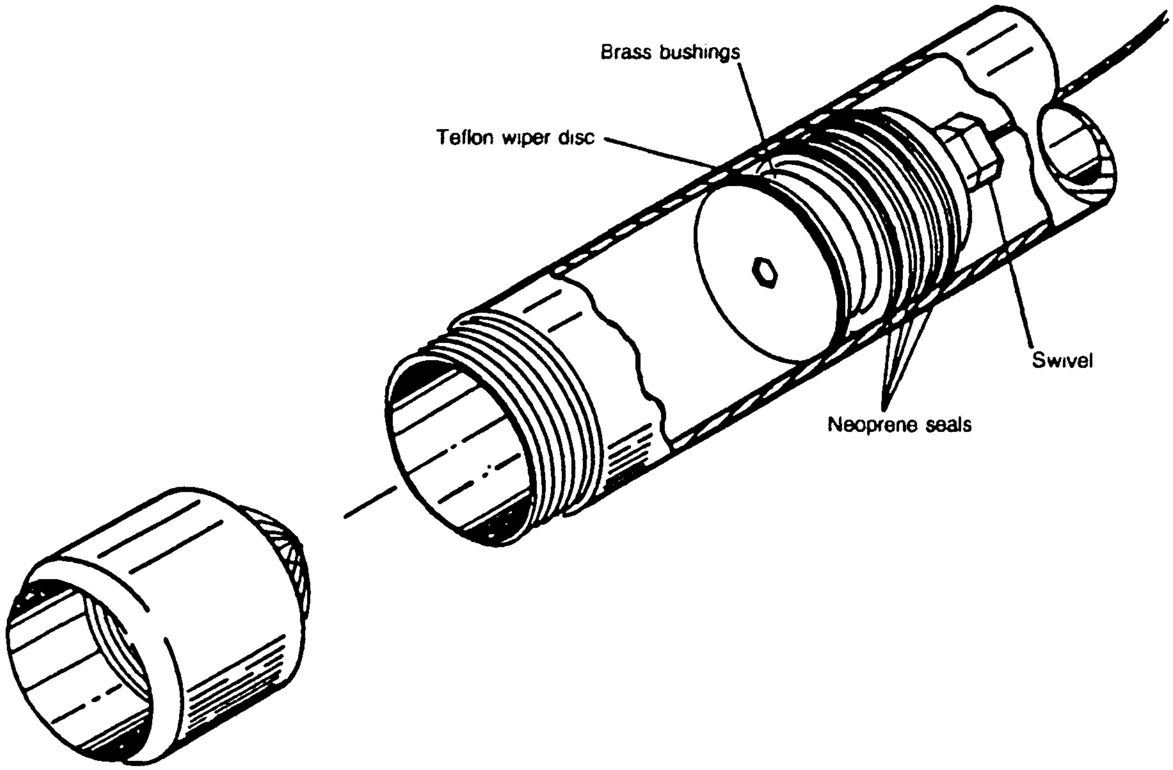

Figure 44. Modified wireline piston sampler (Leach et al., 1988).

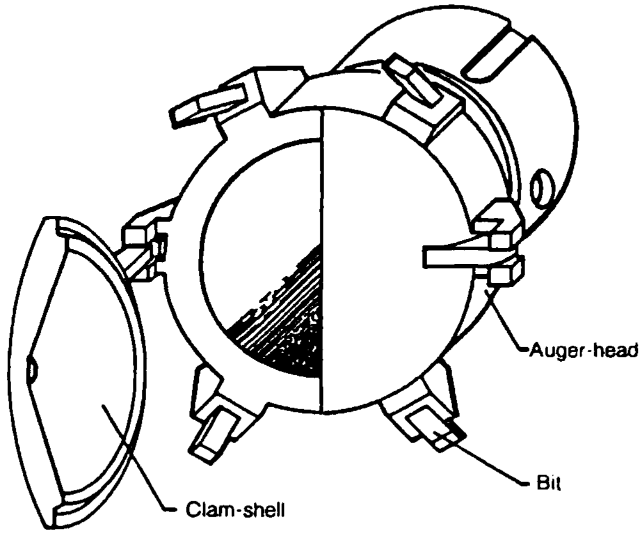

Figure 45. Clam-shell fitted auger head (Leach et al., 1988).

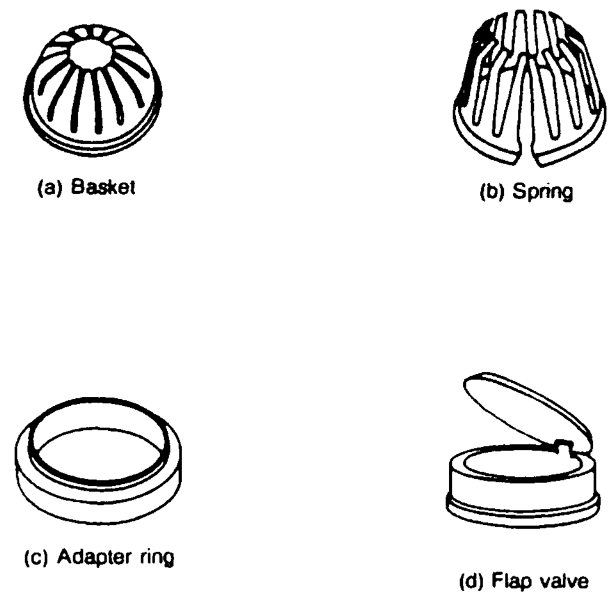

Figure 46. Types of sample retainers (Mobile Drilling Company, 1982).

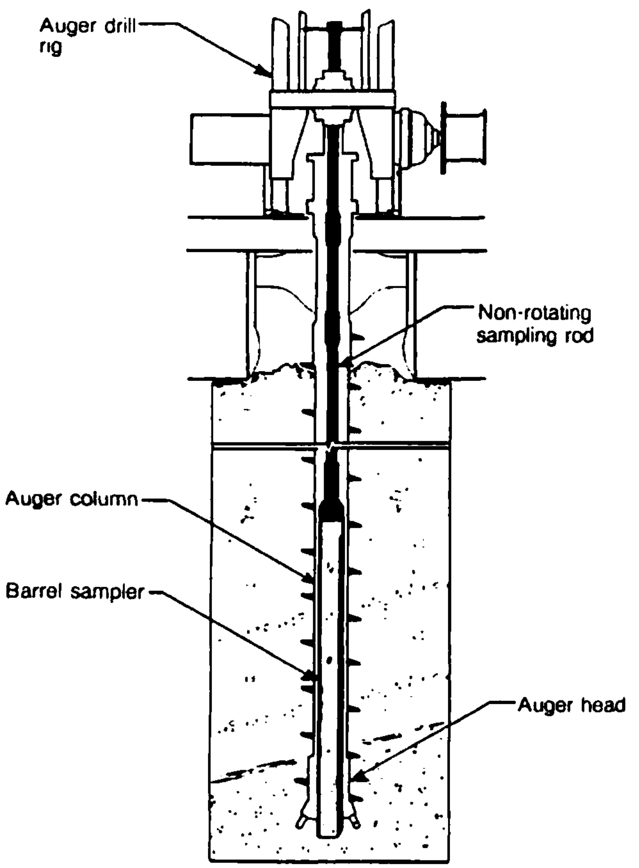

Figure 47. Diagram of a continuous sampling tube system (after Central Mine Equipment Company, 1987).

3) relative drilling cost,
4) availability of drilling equipment,
5) relative time required for well installation and development,
6) ability of drilling technology to preserve natural conditions,
7) ability to install design diameter of well and
8) relative ease of well completion and development.

A complete discussion of the importance of these factors can be found in this section under the heading entitled "Criteria For Evaluating Drilling Methods."

Each matrix has three main parts (Figure 49). The top section of the page contains a brief description that delineates which unique combination of general hydrogeologic conditions and well design requirements apply to evaluations made in that matrix. The middle of the page contains a chart that lists the ten drilling methods on the vertical axis and the eight criteria for evaluating the drilling methods on the horizontal axis. This chart includes relative judgments, in the form of numbers, about the applicability of each drilling method. The bottom of the page contains explanatory notes that further qualify the general hydrogeologic conditions and well design requirements that have influence on the development of the numerical scheme in the chart.

The numbers in the charts are generated by looking at each of the criteria for evaluating drilling methods and evaluating each drilling method on that one criteria with respect to the conditions dictated by the prescribed five general hydrogeologic conditions and well design requirements. The most applicable drilling method is assigned a value of 10 and the other drilling methods are then evaluated accordingly. The process always includes assigning the number 10 to a drilling method. Once each of the criteria is evaluated, the numbers for each drilling method are summed and placed in the total column on the right. Where a drilling method is not applicable, the symbol, "NA," for not applicable, is placed in the row for that drilling method.

How To Use the Matrices

The matrices are provided as an aid to the user when selecting the appropriate drilling technique under selected conditions. The user should begin by referring to Table 2 and choosing the number of the matrix that most closely parallels the hydrogeologic conditions at the site and that has the same anticipated well depth and casing diameter requirements. The user should then refer to that matrix in Appendix B, read the explanatory notes and refer to the relative values in the "total" column of the matrix. Explanatory text for both the drilling methods and the criteria for evaluating drilling methods should be reviewed to understand the assumptions and technical considerations included in the relative numbers.

How To Interpret a Matrix Number

The numbers contained in the "total" column of the chart represent a relative indication of the desirability of each drilling method for the prescribed conditions of the matrix. Higher total numbers indicate more appropriate drilling methods for the specified assumptions. When numbers are relatively close in value, drilling methods may be almost equally as favorable. Where numbers range more widely in value, the matrix serves as a relative guide for delineating a favorable drilling method. The numbers cannot be compared between matrices; numerical results are meaningful only when compared on the same chart. The purpose of the numerical rating is to provide the user with a relative measure of the applicability of drilling methods in specific situations.

Once the user consults the matrix for a preliminary evaluation, it is necessary to reevaluate the numbers in terms of the factors that locally impact the ultimate choice of a drilling method: equipment availability and relative drilling cost. A drilling method might be indicated as the most favorable technique according to the matrix totals, but the equipment may not be available or the cost factor may be prohibitive. In these situations, an alternative drilling method will need to be chosen or the design criteria modified. The drilling costs have been evaluated in the matrix based on relative national costs. Recognizing that relative costs may vary, the user of the matrix should look carefully at the relative cost column to determine if the relative costs are applicable for the specific geographic location of interest. Adjustments should be made if costs differ significantly.

Criteria for Evaluating Drilling Methods

In determining the most appropriate drilling technology to use at a specific site the following criteria must be considered.

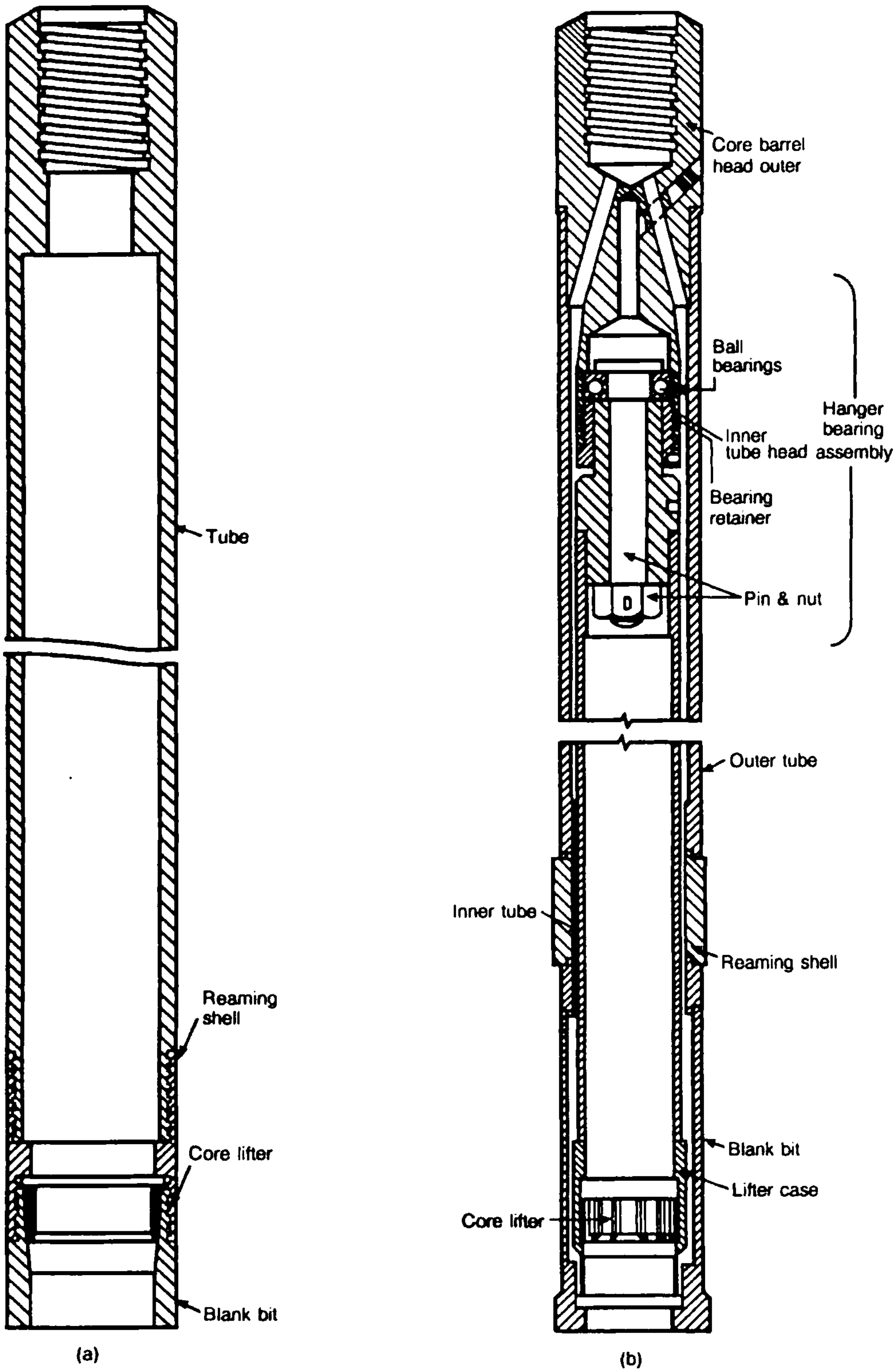

Figure 48. Diagram of two types of core barrels:
a) single tube and b) double-tube (Mobile Drilling Company, 1982).

MATRIX NUMBER 1

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid permitted; casing diameter 2 inches or less; total well depth 0 to 15 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	1	5	9	10	5	9	6	4	49
Driving	1	1	10	10	5	5	1	4	37
Jetting	2	1	8	10	5	1	1	1	29
Solid Flight Auger	3	4	7	9	10	4	5	2	44
Hollow Stem Auger	10	10	9	9	10	8	10	9	75
Mud Rotary	8	10	8	10	7	4	10	5	62
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	7	5	6	4	6	9	10	10	57
Dual Wall Rotary	7	8	6	1	6	9	10	9	56
Cable Tool	9	10	5	7	4	10	10	10	65

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. The shallow depth of up to 15 feet, and small completed well diameter of 2 inches or less allows maximum flexibility in equipment.
5. Samples collected in solid flight auger, hollow-stem auger, mud rotary and cable-tool holes are taken by standard split-spoon (ASTM D1586) or thin-wall sampling (ASTM D1587) techniques, at 5-foot intervals.

Figure 49. Format for a matrix on drilling method selection.

These criteria must encompass both hydrogeologic settings and the objectives of the monitoring/drilling program.

Versatility of the Drilling Equipment and Technology with Respect to the Hydrogeologic Conditions at the Site

The drilling equipment must effectively deal with the full range of conditions at each site and also allow the satisfactory installation of well components as designed. The choice of proper drilling techniques requires specific knowledge of: 1) the objectives of the monitoring well, including desired well depth and casing diameter, 2) the type(s) of geologic formations to be penetrated and 3) the potential borehole instability and/or completion difficulties. Additional factors that influence the choice of a drilling method include: 1) saturation or unsaturation of the zone(s) to be drilled, 2) necessity to install a filter pack in the monitoring well and 3) potential adverse effects on the final monitoring program by drilling fluid invasion into the monitored zone.

The interaction between the geologic formations, hydrologic conditions and the equipment to be used is best illustrated by example. After reviewing the discussion of drilling methods in the beginning of this section, it should be obvious that hollow-stem augers can be used effectively in unconsolidated materials, but are not applicable to the installation of monitoring wells in solid rock such as granite. It may be less obvious that drilling through the saturated, unstable overburden overlying solid rock, such as granite, may be very difficult with the air rotary technique; however, the air rotary technique would be very effective in drilling the granite. The overburden, conversely, can be very effectively dealt with by hollow-stem augers.

If the monitoring objectives in this illustration include pumping at relatively high rates, then a 4-inch or larger casing may be required. The installation of the casing mandates the use of a large inside diameter hollow-stem auger unless the overburden is sufficiently stable to permit open-hole casing installation. If either the casing diameter is too large or the depth is too great, then hollow-stem augers are not appropriate and an alternative drilling technique (e.g. mud rotary, cable tool, drill through casing hammer, etc.) must be evaluated. Thus, judgment has to be made for each site whether or not the preferred drilling technology can deal with the extant hydrogeologic conditions and the objectives of the monitoring program.

Reliability of Formation (Soil/Rock/Water) Samples Collected During Drilling

The purpose of a monitoring well is to provide access to a specific zone for which water level (pressure head) measurements are made, and from which water samples can be obtained. These water samples must accurately represent the quality of the water in the ground in the monitored zone. To this end, it is essential to acquire accurate, representative information about the formations penetrated during drilling and specifically about the intended monitored zone. Sample reliability depends partially on the type of samples that can be taken when using various drilling techniques. The type of samples attainable and the relative reliability of the samples are summarized in Table 19 and discussed below in terms of drilling methods. An additional discussion of sampling techniques is found in the section entitled "Soil Sampling and Rock Coring Methods."

Hand Auger —

Soil samples that are taken by hand auger are disturbed by the augering process and are usually collected directly from the cutting edge of the auger. Deeper samples may be non-representative if sloughing of shallow materials occurs. Drilling by hand auger is usually terminated when the saturated zone is encountered. It is possible to continue drilling below the saturated zone in some situations by adding water and/or drilling mud. However, when water and/or drilling mud are added, reliable samples cannot usually be obtained. An additional discussion of hand augering can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Driven Wells —

No samples can be taken during the construction of a driven well, although some interpretation of stratigraphic variation can be made from the driving record. Water-quality samples can be obtained in any horizon by pumping from that depth of penetration. An additional discussion of driven wells can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Jet Percussion —

Neither valid soil samples nor valid water samples can be obtained during the construction of wells by this method. Only gross lithology can be observed in the material that is washed to the surface during the jetting procedure. An additional discussion of jet percussion drilling can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Solid Flight Augers —

Soil samples collected from solid, continuous flight augers are rotated up the auger flights to the surface during drilling or scraped from the auger flights upon extraction. The disturbed samples from either of these sources provide samples of moderate quality down to the first occurrence of water, and generally unreliable samples below that level.

More valid samples can be obtained where the borehole is stable enough to remain open. In this situation, the auger flights can be removed from the borehole and samples can then be taken by either split-spoon (ASTM D1586) or thin-wall (ASTM D1587) sampling techniques. It is generally not possible to use these techniques in saturated formations with the augers removed because the borehole frequently collapses or the bottom of the borehole "heaves" sand or silt upward into the open borehole. The heaving occurs as a consequence of differential hydrostatic pressure and is exacerbated by the removal of the augers. When caving or heaving occurs, it is very difficult to obtain reliable samples. An additional discussion on solid-flight augers can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Hollow-Stem Augers —

Where samples are collected from depths of less than 150 feet, the hollow-stem auger technique is the method most frequently used to obtain samples from unconsolidated formations. Samples may be taken through the hollow-stem center of the augers by split-spoon (ASTM D1586), thin-wall (ASTM D1587) or wireline piston sampling methods (refer to Figures 40 through 44). The maximum outside diameter of the sampler is limited by the inside diameter of the hollow stem. If 3.25-inch inside diameter augers are being used, then a maximum 3-inch outside diameter sampler can be used and must still retain the requisite structural strength and meet the requirement to optimize (minimize) the area ratio. An additional discussion on soil sampling can be found in the section entitled "Soil Sampling and Rock Coring Methods."

The rotation of the augers causes the cuttings to move upward and debris to be ground and "smeared" along the borehole in the thin annular zone between the borehole wall and the auger flights. This smearing has both positive and negative connotations. Because the movement of debris is upward, the cuttings from the deeper zones may seal off shallower zones. This minimizes cross-connection of fluids from shallow to deep zones, but increases the possibility of deep to shallow contamination. Shallow zones that may have been penetrated in the upper portion of the borehole are also difficult to develop once smearing occurs. With the shallow zones sealed off by cutting debris and with the auger flights serving as temporary casing, it is often possible to obtain valid formation samples of discrete saturated zones as they are initially penetrated.

Water samples are difficult to obtain in the saturated zone during drilling due to formation instability. A special type of lead auger flight has been designed to overcome the problem of collecting water samples concurrent with drilling and to make it possible to sample and/or pump test individual zones as the augers are advanced. This specially reinforced screened auger serves as the lead, or lowermost, auger and is placed just above the cutting head (Figure 28). This screened section can be used to temporarily stabilize the borehole while a small-diameter pump or other sampling device is installed within the hollow stem. Appropriate testing can then be performed. The advantage of this technique is low-cost immediate data and water sample acquisition during drilling. The major disadvantages are: 1) doubt about cross-connection of zones and ultimate data validity and 2) the risk of losing both the equipment and the borehole if extremely difficult drilling conditions are encountered since there is some structural weakness in the screened section. An additional discussion of hollow-stem augers can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Direct Mud Rotary Drilling —

A variety of sampling technologies can be used in concert with mud rotary drilling techniques. These include: 1) grab or ditch samples from circulated cuttings, 2) split-spoon and thin-walled samples in unconsolidated materials and 3) single and double-tube conventional core barrels in consolidated materials. In direct rotary drilling, the functions of the drilling fluid are to: 1) lubricate and cool the bit, 2) remove fragmentary particles as they are loosened and 3) stabilize the borehole. The cuttings are typically circulated up the borehole, through a pipe or ditch, into a temporary settling tank or pit. The drilling fluid is then circulated back down the drill pipe (Figure 29).

Samples taken from the ditch or settling pond (mud pit) are therefore a composite of: 1) materials cut a few minutes earlier (time lag varies with depth, borehole size, drill pipe and pump rate), 2) any unstable materials that have washed or fallen into the borehole from a shallower zone and 3) any re-circulated materials that failed to settle out during earlier circulation. These materials are mixed with the drilling fluid and any additives used during the drilling process. The interpretation of these samples requires experience and even then the interpretation is questionable. Ditch samples are frequently collected in the petroleum industry, but have little practical value in the effective installation of monitoring wells. Thin, stratified zones that require specific monitoring are difficult to identify from ditch samples.

Both split-spoon (ASTM D1586) and thin-wall samples (ASTM D1587) can be obtained while using direct rotary drilling methods in unconsolidated materials. At shallow depths, samples are taken through the drill bit in exactly the same manner as previously described for hollow-stem augers. Corresponding size limitations and sampling problems prevail.

As depths increase below about 150 feet, the time consumed in taking split-spoon and thin-wall samples becomes excessive and wireline sampling devices are used to collect and retrieve samples. Samples can be taken either continuously or intermittently. In unconsolidated materials, wireline samplers can collect only disturbed samples and even then there are recovery problems and limitations for both fine and coarse-grained materials. In consolidated rock the best samples can be obtained by coring.

A significant advantage of drilling with a good drilling mud program is that typically the open borehole can be stabilized by the drilling mud for a sufficient period of time to remove the drilling tools and run a complete suite of geophysical logs in the open hole. This information is used in concert with other data (i.e., the drilling time log, the sample log, fluid loss or gain information and drilling characteristics) to provide definitive evaluation of formation boundaries and to select screen installation intervals.

When attempting to define the in-situ properties of unconsolidated materials, drilling by the mud rotary method offers another advantage. Because the drilling mud maintains the stability of the borehole, samples taken by split-spoon or thin-wall methods ahead of the drill bit tend to be much more representative of indigenous formation conditions than those samples taken, for example, during hollow-stem auger drilling. In auger drilling it is sometimes *very* difficult to obtain a sample from below the cutting head that has not been affected by the formation heaving upward into the open borehole.

If the drilling fluid is clear water with no drilling additives, then it may be difficult to maintain borehole stability because little mudcake accumulates on the wall of the borehole. In this case, the loss or gain of water while drilling is an indication of the location of permeable zones.

Because drilling fluid is used to drill the borehole and because this fluid infiltrates into the penetrated formations, limited water-quality information can be obtained while drilling. Drilling mud seals both high and low-pressure zones if properly used. However, this sealing action minimizes interaquifer cross-contamination while drilling. Before any zone provides representative samples, *all* drilling mud and filtrate should be removed from the formation(s) of interest by well development.

The most common additives to drilling mud are barite (barium sulfate) for weight control and sodium montmorillonite (bentonite) for viscosity and water loss control. Both can alter indigenous water quality.

Bentonite is extremely surface active and forms clay/organic complexes with a wide range of organic materials. The water used to mix the drilling mud is potentially interactive both with the drilling mud and with the water in the formation. At the very least, the drilling fluid dilutes the formation water that is present prior to the drilling activity. For these reasons it is very difficult, if not impossible, to be confident that sufficient development has been performed on a direct rotary-drilled monitoring well, and that the water quality in a particular sample is truly representative of the water quality in place prior to the construction of the well.

Where very low concentrations of a variety of contaminants are being evaluated and where the potential reactions are undefined, it is not recommended that drilling fluid be used during monitoring well installation. This same concept applies to boreholes drilled by cable tool and/or augering techniques where drilling fluid is necessary for borehole stability. Where drilling mud is used, monitoring well development is continued until such time as a series of samples provides statistical evidence that no further changes are occurring in key parameters. When this occurs, the resultant quality is considered to be representative (Barcelona, et al., 1985a). An additional discussion of drilling fluids can be found in the section entitled "Drilling Fluids."

Water-level measurements of different zones penetrated cannot be determined while drilling with direct rotary methods. Accurate water levels can only be determined by installing, screening and developing monitoring wells in the specific zones of interest. An additional discussion on direct mud rotary drilling can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Air Rotary —

Direct air rotary is restricted in application to consolidated rock. Where the bedrock is overlain by unconsolidated materials, a borehole can be drilled and sampled by alternative methods including: 1) roller-cone bit with water-based fluid, 2) air with a casing driver, 3) cable tool or 4) augering. Formation samples are taken by the appropriate methods discussed in the related sections of this discussion. Once surface casing is installed and sealed into bedrock, the underlying bedrock can be successfully drilled using air rotary methods.

When using air rotary drilling in semi-consolidated and consolidated materials, air is circulated down the drill pipe and through the bit. The air picks up the cuttings and moves the cuttings up through the annular space between the drill pipe and the wall of the borehole. If the formations drilled are dry, the samples reach the surface in the form of dust. By injecting water or a mixture of water and surfactant (foam): 1) dust is controlled, 2) regrinding of samples is minimized and 3) the sizes of individual particles are increased sufficiently to provide good formation samples. Because the injected water/foam is constantly in motion and supported by the air, there is only a slight possibility of water loss or formation contamination during drilling.

After water is encountered in the borehole, further injection of water from the surface can often be eliminated or minimized and good rock fragments can be obtained that are representative of the formations penetrated. Samples obtained in this manner are not affected by the problems of recirculation, lag time and drilling fluid contamination that plague sample evaluation when drilling mud is used. Air may cause changes in the chemical and biological activity in the area adjacent to the borehole. Examples of quality changes include oxidation and/or stripping of volatile organic chemicals. The time required for these changes to be reversed varies with the hydrogeologic and geochemical conditions. Because the rock boreholes are generally stable and penetration rates are high, there is minimal contamination from previously-drilled upper zones. Water-quality samples and water levels can be easily obtained from the first saturated zone penetrated, but this zone must be cased if subsequent zones are to be individually evaluated.

For monitoring well installation, the injected air must be filtered prior to injection to prevent contamination of the borehole by oil exhausted by the air compressor. Because a down-the-hole hammer requires lubricating oil for operation, it has more limitations for monitoring well installation. An additional discussion on air rotary drilling can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Air Rotary with Casing Driver —

Unconsolidated formations can be drilled and sampled by combining air rotary drilling with a casing driver method. In this procedure the drill bit is usually extended approximately one foot below the bottom of the open casing, and the casing is maintained in this position as the drill bit is advanced (Figure 33). The casing is either large enough to permit retraction of the bit, in which instance the casing must be driven through the undergauge hole cut by the bit; or an underreamer is used, and the casing moves relatively easily down into the oversized borehole. Generally, the undergauge procedure is favored for sampling unconsolidated formations, and the underreamer is favored for semi-consolidated formations. Either technique allows good samples to be obtained from the freshly-cut formation and circulated up the cased borehole. If chemical quality of the formation sample is important, particularly with regard to volatile organics or materials that can be rapidly oxidized, then air drilling may not be appropriate. When the casing is advanced coincident with the deepening of the borehole, the sample collection procedures and the sample quality are very similar to those prevailing with the use of direct air rotary. An additional discussion on air rotary with casing driver can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Dual-Wall Reverse Circulation Rotary —

In dual-wall reverse circulation rotary drilling, either water or air can be used as the circulation medium. The outer wall of the dual-wall system serves to case the borehole. Water (or air) is circulated down between the two casing walls, picks up the cuttings at the bottom of the borehole, transports the cuttings up the center of the inner casing and deposits them at the surface. Because the borehole is cased, the samples collected at the surface are very reliable and representative of the formations penetrated. Sample collection using dual-wall rotary has the following advantages: 1) third stratigraphic zones often can be identified; 2) contamination of the borehole by drilling fluid is minimized; 3) interaquifer cross-contamination is minimized; 4) individual zones that are hydraulically distinct can be identified with specific water levels, and discrete samples often can be collected if sufficient time is allowed for recovery; 5) in low hydraulic pressure formations, air pressure within the borehole may prevent the formation water from entering the borehole and 6) sampling at the surface can be continuous. Split-spoon samples can also be collected through the bit. One disadvantage is that because the outer casing is removable and not sealed by grout, hydraulic leakage can occur along the outside of the unsealed casing.

Water or foam can be injected to increase the penetration rate and improve sample quality. An additional discussion of dual-wall reverse circulation rotary drilling can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Cable Tool —

When drilling in saturated, unconsolidated sand and gravel, good quality disturbed samples can be obtained by the cable tool "drive and bail" technique. In this technique, casing is driven approximately 2 to 5 feet into the formation being sampled. The sample is then removed from the casing by a bailer. For best sample quality, a flat-bottom bailer is used to clean the borehole (Figure 36). The entire sample is then collected at the surface, quartered or otherwise appropriately split and made available for gradation analyses. When drilling in unsaturated material, water must be added to the borehole during drilling and sampling.

The drive and bail technique is often the best method for sampling well-graded or extremely coarse-grained deposits because both coarse and fine-grained fractions are collected during sampling. Large-diameter casing can be driven and large bailers can be used. The most common size range for casing is from 6 inches to 16 inches although larger sizes are available. For the drive and bail technique to be effective, excessive heaving of the formation upward into the casing during cleanout must be prevented. This can usually be controlled by: 1) overdriving the casing, thereby maintaining a "plug" of the next sample in the casing at all times, 2) careful operation of the bailer and 3) adding water to the borehole to maintain positive hydraulic head within the borehole.

During drive and bail-type drilling, split-spoon (ASTM D1586) and thin-wall (ASTM D1587) samples can be collected after cleaning out the casing with the bailer. Samples are collected ahead of the casing by inserting conventional sampling tools inside the casing. This technique permits sampling of fine-grained, unconsolidated formations.

The quality of cable tool samples from consolidated formations varies with drilling conditions. When the bedrock is saturated, good broken chips of the formation can be obtained by bailing at frequent intervals. If the chips remain in the borehole too long or if sufficient lubrication is lacking, the samples are re-ground to powder.

When drilling by cable tool techniques and using a good casing program, it is usually possible to identify and isolate individual water-bearing units as they are drilled. This provides the opportunity to obtain good water-level and water-quality data. An additional discussion on cable tool drilling can be found in the section entitled "Drilling Methods for Monitoring Well Installation."

Relative Drilling Costs

Drilling and completion costs vary for individual methods with each set of general conditions and well design requirements. For example, the cost of drilling and sampling with the hollow-stem auger method may be much higher for a dense, bouldery till than it is for a similar depth in saturated, medium-soft lake clays. The cost of installing nominal 2-inch diameter casing and screen within hollow-stem augers varies with depth and borehole stability.

The relative drilling cost ratings shown on each matrix apply to the broad range of conditions included within each set of general conditions and well casing requirements. The relative ratings reflect the total cost of drilling, sampling, casing, screening, filter-packing, grouting, developing and surface protecting the monitoring well. Equivalent costs of mobilization and access are assumed. Relative ratings are based on consideration of the average costs when compared to the other methods of drilling throughout the continental United States. Local cost variations can be significantly influenced by equipment availability and can cause variation in these relative ratings. Where local costs vary from the ratings shown, an adjustment should be made to the specific matrix so that the actual costs are more accurately reflected.

Availability of Equipment

The ratings shown in the matrices for equipment availability are based on the general availability of the drilling equipment throughout the United States. The availability of specific equipment on a local basis may necessitate the revision of the rating in the matrix to make the rating more representative.

The type of equipment most generally available for monitoring well installation is the direct mud rotary drilling rig. Direct mud rotary techniques are applicable to water supply wells, gas and oil exploration and development and soil testing. As a result, this equipment is widely available throughout the country.

Solid-flight and hollow-stem augering equipment is also generally available throughout all regions where unconsolidated materials predominate. The portability of augering equipment and the prevalent use of augers in shallow foundation investigations have increased auger availability to almost all areas.

Air rotary drilling has primary application in consolidated rock. Availability of equipment is greatest in those consolidated rock areas where there are mining exploration, water-supply production activities or quarrying applications. The availability of this equipment is greatest in: 1) the western mountainous area, 2) the northeast and 3) the northwest parts of the country.

Casing drivers used in combination with direct air rotary drilling are somewhat sparsely, but uniformly distributed throughout all regions. Versatility in screen installation, casing pulling and application in unconsolidated materials have broadened the use of air rotary with casing driver techniques.

Dual-wall rotary drilling is becoming increasingly popular because the technique can be used in a wide range of both consolidated and unconsolidated formations. Availability is generally restricted to the west-central and southwestern parts of the country.

Cable tool equipment availability is limited in many portions of the south, southeast, southwest, west and northwest. It is generally available in the north-central and northeastern portions of the country.

Relative Time Required for Well Installation and Development

The time required for drilling the well, installing the casing and screen and developing the well can be a significant factor when choosing a drilling method. For example, if a relatively deep hole drilled with cable tool techniques takes several days, weeks or longer, there may be significant scheduling disadvantages. If longer-term supervision is required, then this additional cost factor must also be taken into account. The excess cost of supervision is not included in the matrix evaluation. Similarly, if a direct mud rotary technique is employed to make a fast installation and an additional three weeks of development is required before a valid sample can be obtained, the advantages of the rapid installation need to be re-evaluated.

Ability of Drilling Technology to Preserve Natural Conditions

Assuming that the purpose of a monitoring well is to provide access to a specific zone for which water-level (pressure head) measurements are to be made, and from which water samples can be obtained to accurately represent the quality of the water in place in the zone being monitored, then it is obviously important that the drilling methodology employed must minimize the disturbance of indigenous conditions or offer a good possibility that indigenous conditions can be restored. To achieve these goals, the drilling methodology should result in minimal opportunity for physical and/or chemical interactions that might cause substantial or unpredictable changes in the quality of the water being sampled. The following discussions present some of the problems and potential problems related to the disturbance of the natural conditions as a consequence of monitoring well drilling and installation:

1) When using drilling mud in the borehole, filtrate from the drilling fluid invades the adjacent formations. This filtrate mixes with the natural formation fluids and provides the opportunity for chemical reaction between the mud filtrate and the formation fluid. If chemical reactions occur, "false" water-quality readings may result. The mixing effect is minimized by good development; potential chemical reactions are more difficult to deal with in a reasonably predictable manner. For example, if a high pH filtrate invades a low pH formation and metals are present in either fluid, precipitation of the metals can be anticipated in the vicinity of the borehole. The metals may subsequently be re-dissolved at an unknown rate, if chemical conditions are not constant. Thus, the drilling fluid filtrate invasion can result in alternately low and high readings of metals at different intervals of time.

2) When a monitoring well is drilled with augers, fine silts and clays commonly smear along the borehole wall and frequently seal the annular space between the augers and the borehole wall. This sealing action can then minimize the cross-connection of discrete zones. However, the fine-grained particulate matter that is smeared into the zone of interest also reduces the flow from that zone, introduces the possibility of cross-contamination from another zone and presents the opportunity for the clays that are smeared into the zone to sorb contaminants and consequently generate non-representative water-quality results. In mud rotary drilling, a mudcake is deposited on the borehole wall. This bentonitic mudcake serves to stabilize the borehole and also has the capacity to sorb both organic and inorganic constituents.

3) During any drilling process physical disruption of the formation occurs and grain-to-grain relationships change. Regardless of whether or not the well is completed with a natural or artificial filter pack, the flow paths to the well are altered; tortuosity is changed; Reynolds numbers are modified with flow path and velocity variations; and equilibrium (if, in fact, the indigenous water is at equilibrium) is shifted. If the formation is permitted to collapse, as may occur in sand and gravel materials, the removal of the collapsed material exacerbates the problem.

   With the changes that occur in the physical setting, it is very difficult to be confident that the water samples subsequently collected from the monitoring well truly reflect conditions in the ground beyond the influence of the disturbed zone around the well. The changes are of particular concern when analyzing for very low concentrations of contamination.

It becomes apparent that a drilling technique that has the least possible disruptive influence on the zone(s) being monitored is preferable in any given setting. The matrices presented indicate the relative impact of the various drilling methodologies for the designated circumstances.

Ability of the Specified Drilling Technology to Permit the Installation of the Proposed Casing Diameter at the Design Depth

The design diameter for the casing and well intakes(s) to be used in any monitoring well depends on the proposed use of the monitoring well (i.e. water-level measurement, high-volume sampling, low-volume sampling, etc.). When installing artificial filter packs and bentonite seals, a minimum annular space 4 inches greater in diameter than the maximum outside diameter of the casing and screen is generally needed. A 2-inch outside diameter monitoring well would then require a minimum 6-inch: 1) outside diameter borehole, 2) auger inside diameter or 3) casing inside diameter for reliable well installation. This need for a 4-inch annular space places a severe limitation on the use of several currently-employed drilling technologies.

For example, hollow-stem augers have been widely used to install 2 3/8-inch outside diameter monitoring wells. A significant portion of this work has been performed within 3 1/4-inch inside diameter hollow-stem augers. At shallow depths, especially less than fifteen feet, it has been possible to install well intake and casing, filter pack, bentonite seal and surface grout within the small working space. However, at greater depths, it is very doubtful if many of these components are truly emplaced as specified. There simply is not sufficient annular clearance to work effectively. For a more complete discussion on filter pack and screen emplacement in hollow-stem augers, refer to Appendix A.

When drilling with direct air rotary with a casing hammer, the maximum commonly-used casing size is 8 inches in diameter. The outside diameter of the monitoring well casing should therefore be 4 inches or less to maintain adequate working space. Because pipe sizes are classified by nominal diameters, the actual working space will be somewhat less than the stated annular diameter unless the actual pipe O.D. is used in calculations.

When drilling through unstable formations with dual-wall reverse circulation methods, the monitoring well casing must be installed through the bit. The hole in the bit barely permits the insertion of a nominal 2-inch diameter casing. This method does not allow the installation of an artificial filter pack because there is no clearance between the bit and 2-inch casing.

The ratings presented in each matrix evaluate the relative ability of the various methodologies to permit the installation of the design casing diameters in the indicated hydrogeologic conditions.

Ease of Well Completion and Development

Well completion and development difficulty varies with: 1) well depth, 2) borehole diameter, 3) casing and well intake diameter, 4) well intake length, 5) casing and well intake materials, 6) drilling technique, 7) mud program, 8) hydrostatic pressure of the aquifer, 9) aquifer transmissivity, 10) other hydrogeologic conditions and 11) geologic conditions that affect the borehole. The relative ease of dealing with these variables by the selected drilling equipment is shown in each matrix for the indicated conditions. For example, where a relatively thin, low-yield aquifer has been drilled with hollow-stem augers, the muddy clay/silt mixture from the borehole tends to seal the zone where the well intake is to be set. The development of this zone is very difficult. If a filter pack has been installed, development becomes almost impossible. If direct mud rotary is used to drill this same low transmissivity zone, and the mudcake from the drilling fluid remains between the filter pack and the borehole wall, very difficult development can be expected. If the borehole is drilled with clear water, development *might* be easier.

For any given scenario a very subtle modification of procedure may make the difference between success and failure. The ratings shown in the matrices are based on general considerations. Their relative values expressed in the table vary in specific circumstances. Most importantly, however, is that an experienced observer be able to make on-site observations and to modify the procedures as the work progresses.

Drilling Specifications and Contracts

The cost of installing a monitoring well depends on several factors including: 1) site accessibility, 2) labor and material costs, 3) well design, 4) well use, 5) well development, 6) well yield and 7) local geologic conditions (Everett 1980). Because these factors are variable, it is important to secure a well contract that addresses these items in a concise and clear format. Proper formatting helps ensure that the well will be constructed as specified in the contract and for the agreed price. In simple terms, a well-written contract is a quality control check on well construction.

Monitoring well contracts are typically written in three major sections including: 1) general conditions, 2) special conditions and 3) technical specifications. General conditions address items related to the overall project performance including: scheduling, materials, equipment, labor, permits, rights of various parties, tests and inspections, safety, payments, contracts, bonds and insurance (Driscoll, 1986). Special conditions detail project-specific and site-specific items including: 1) a general description of the purpose and scope of the work, 2) work schedule, 3) insurance and bond requirements, 4) pertinent subsurface information, 5) description of necessary permits, 6) information on legal easements, 7) property boundaries and utility location and 8) a description of tests to be performed and materials to be used during the project (United States Environmental Protection Agency, 1975). If general and special conditions appear to conflict, special conditions of the contract prevail (Driscoll, 1986). Technical specifications contain detailed descriptions of dimensions, materials, drilling methods and completion methods.

Most contracts are awarded as part of a bidding process. The bidding process may be either competitive or non-competitive. In a competitive bidding process, contractors are asked to submit cost estimates based on a set of specifications for drilling the monitoring wells. The specifications are developed prior to the request for cost proposal by either the client or a consultant to the client. Suggested areas that should specifically be addressed in the specifications are listed in Table 22.

Table 22. Suggested Areas to be Addressed in Monitoring Well Bidding Specifications

Scope of Work
Site Hydrogeology
- existing reports
- well logs
- depth of wells

Schedule of Work Dates
Well Drilling Installation
- materials
- drilling method(s)
- annular seal installation
- development
- protective equipment
- disposal of cuttings

Record-Keeping and Requirements
Sampling Requirements and Procedures
Site Access
- road construction
- tree clearing
- drainage
- leveling

Decontamination of Equipment
- procedures
- materials
- disposal of cuttings and liquids

Site Safety
- equipment
- training

Conditions
- permits
- certificates
- utility location
- site clean up
- procedures for drilling difficulties
- non-functioning wells
- government forms required
- client's right to vary quantities or delete items

Payment Procedures

After cost estimates are obtained, a contractor is selected based on qualifications and pricing. Although some contracts are awarded by choosing the lowest bidder, this practice is not suggested unless the qualifications of the contractor indicate that a quality job can be performed. It is good policy to meet with the selected bidder prior to signing the contract and clarify every technical point and related unit cost. This understanding, duly noted by minutes of the meeting, can eliminate costly errors and misunderstandings. An inspection of the contractor's equipment that will be used on the job should also be made.

Qualifications of contractors are often evaluated during a prequalification process. A contractor prequalifies by submitting information about previous job experience that is related to the scope of work. The prequalification process allows the client to accept bids only from contractors that demonstrate specific qualifications to perform the job. This process helps to ensure that the monitoring wells will be installed by competent contractors. When subcontractors for drilling or supplies are to be employed, the list of subcontractors should also be approved prior to the contract award.

Another way to avoid misunderstandings during the bidding process is to hold a bidders meeting. In a bidders meeting, the potential contractors meet in a group forum with the client to discuss the overall scope of the proposed work and to discuss specifications for monitoring well installation. Any questions about the specifications or problems with performance according to the specifications can be discussed and resolved prior to proposal submission. All information must be provided equally to all prospective bidders.

In non-competitive bidding, cost estimates are provided by only one contractor. Because the procedure may be less formal, the contractor may play a more active role in developing the monitoring well specifications and presenting a cost estimate. However, a less formal process may also mean that written specifications for monitoring well installation may never be developed. This situation should be avoided to help ensure that the monitoring wells are constructed properly.

Cost proposals can be submitted in a variety of formats including: 1) fixed price, 2) unit price and 3) cost plus. Fixed-price contracts list the manpower, materials and additional costs needed to perform the work and specify a fixed price that will be paid upon completion of the work. Unit price contracts are similar, but establish a fixed price for each unit of work that is performed. Cost-plus contracts list specific costs associated with performing the work and include a percentage of those costs as an additional amount that will be paid to perform a job. A percentage listed in a cost-plus contract is typically viewed as the profit percentage being proposed by the contractor. In fixed-price and unit-price proposals, the profit percentage is included as part of the itemized pricing structure.

To ensure that the monitoring well is constructed according to the intent of the specifications, the contract should be very specific and list all necessary items and procedures so that nothing is left to interpretation or imagination. This clarity can best be obtained by listing individual pay items instead of combining items into unspecified quantities in lump sum pricing. Suggested items that should specifically be addressed in the contract on a unit price basis are listed in Table 23.

The bidder should also be required to supply information on: 1) estimated time required for job completion, 2) date available to start work, 3) type and method of drilling equipment to be used and 4) insurance coverage. A pay item system may also reduce the need for change during the drilling process by further clarifying the procedures to be used (Wayne Westberg, M-W Drilling, Inc., personal communication, 1986). A change order is a written agreement from the purchaser to the contractor authorizing additions, deletions or revisions in the scope of work, or an adjustment in the contract price or effective period of the contract (United States Environmental Protection Agency, 1975). The contract should specify what payment provisions

Table 23. Suggested Items for Unit Cost in Contractor Pricing Schedule

Item	Pricing Basis
•Mobilization	lump sum
•Site preparation	lump sum
•Drilling to specified depth	per lineal foot or per hour
•Sampling	each
•Material supply	
surface casing	per lineal foot
well casing	per lineal foot
end caps	each
screen	per lineal foot
filter material	per lineal foot or per bag
bentonite seal(s)	per lineal foot
grout	per lineal foot or per bag
casing protector	each
•Support equipment	
water truck and water	lump sum
bulldozer	per hour
•Decontamination	lump sum
•Standby	per hour
•Field expenses	per man day or lump sum
•Material installation	per hour or lump sum
•Well development	per hour or lump sum
•Demobilization	lump sum
•Drilling cost adjustment for variations in depths	± per foot

will be made if the monitoring well cannot be completed as specified. The contract should also define who bears the costs and what the basis for payment will be when drilling difficulties are encountered that were not anticipated in the pricing schedule.

After the contract is signed and work is scheduled to begin, a predrilling meeting between the supervising geologist and the driller should be held to discuss operational details. This meeting reduces the opportunity for misunderstanding of the specifications and improves project relationships.

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Section 5
Design Components of Monitoring Wells

Introduction

It is not possible to describe a "typical" ground-water monitoring well because each monitoring well must be tailored to suit the hydrogeologic setting, the type of contaminants to be monitored, the overall purpose of the monitoring program and other site-specific variables. However, it is possible to describe the individual design components of monitoring wells. These design components may be assembled in various configurations to produce individual monitoring well installations suited to site-specific conditions. Figure 21 illustrates the monitoring well design components that are described in this chapter.

Well Casing

Purpose of the Casing

Casing is installed in a ground-water monitoring well to provide access from the surface of the ground to some point in the subsurface. The casing, associated seals and grout prevent borehole collapse and interzonal hydraulic communication. Access to the monitored zone is through the casing and into either the open borehole or the screened intake. The casing thus permits piezometric head measurements and ground-water quality sampling.

General Casing Material Characteristics

Well casing can be made of any rigid tubular material. Historically, the selection of a well casing material (predominantly for water supply wells) focused on structural strength, durability in long-term exposure to natural ground-water environments and ease of handling. Different materials have demonstrated versatility in well casing applications. In the late 1970s, questions about the potential impact that casing materials may have on the chemical integrity or "representativeness" of a ground-water sample being analyzed in parts per million or parts per billion were raised. Today the selection of appropriate materials for monitoring well casing must take into account several site-specific factors including: 1) geologic environment, 2) natural geochemical environment, 3) anticipated well depth, 4) types and concentrations of suspected contaminants and 5) design life of the monitoring well. In addition, logistical factors must also be considered including: 1) well drilling or installation methods, 2) ease in handling, 3) cost and 4) availability.

The most frequently evaluated characteristics that directly influence the performance of casing materials in ground-water monitoring applications are: 1) strength and 2) chemical resistance/interference. These characteristics are discussed in more detail below.

Strength-Related Characteristics —

Monitoring well casing must be strong enough to resist the forces exerted on it by the surrounding geologic materials and the forces imposed on it during installation (Figure 50). The casing must also exhibit structural integrity for the expected duration of the monitoring program under natural and man-induced subsurface conditions. When casing strength is evaluated, three separate yet related parameters are determined: 1) tensile strength, 2) compressive strength and 3) collapse strength.

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

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

Equally important with tensile strength is the final strength-related property considered in casing selection -- collapse strength. Collapse strength is defined as the capability of a casing to resist collapse by any and all external loads to which it is subjected both during and after installation. The resistance of casing to collapse is determined primarily by outside diameter and wall thickness. Casing collapse strength is proportional to the cube of the wall thickness. Therefore, a small increase in

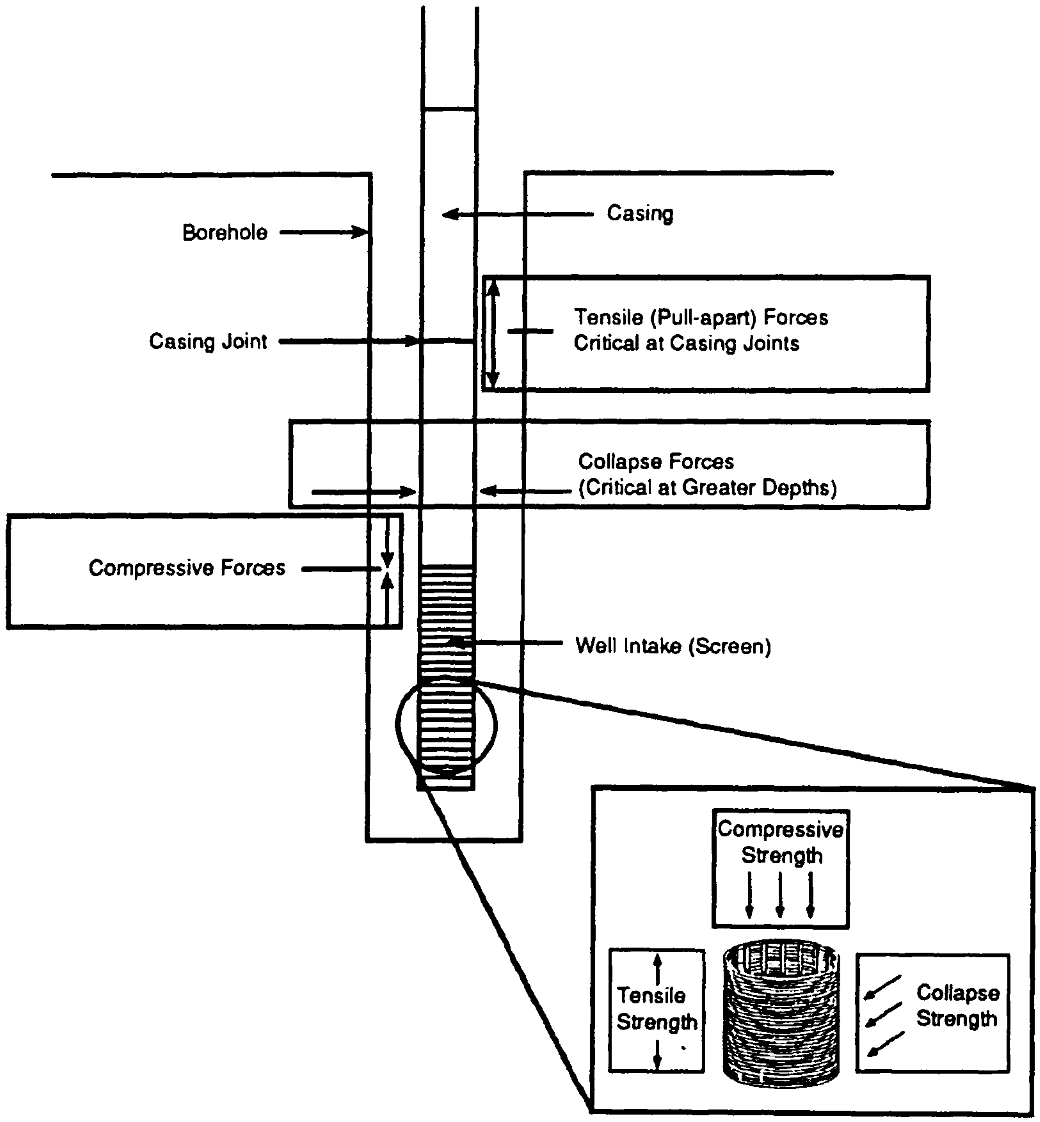


Figure 50. Forces exerted on a monitoring well casing and screen during installation.

wall thickness provides a substantial increase in collapse strength. Collapse strength is also influenced by other physical properties of the casing material including stiffness and yield strength.

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

1) net external hydrostatic pressure produced when the static water level outside of the casing is higher than the water level on the inside;
2) unsymmetrical loads resulting from uneven placement of backfill and/or filter pack materials;
3) uneven collapse of unstable formations;
4) sudden release of backfill materials that have temporarily bridged in the annulus;
5) weight of cement grout slurry and impact of heat of hydration of grout on the outside of a partially water-filled casing;
6) extreme drawdown inside the casing caused by over pumping;
7) forces associated with well development that produce large differential pressures on the casing; and
8) forces associated with improper installation procedures where unusual force is used to counteract a borehole that is not straight or to overcome buoyant forces.

Of these stresses, only external hydrostatic pressure can be predicted and calculated with accuracy; others can be avoided by common sense and good practice. To provide sufficient margin against possible collapse by all normally-anticipated external loadings, a casing should be selected such that resistance to collapse is more than required to withstand external hydrostatic pressure alone. Generally, a safety factor of at least two is recommended (National Water Well Association and Plastic Pipe Institute, 1981). According to Purdin (1980), steps to minimize the possibility of collapse include:

1) drilling a straight, clean borehole;
2) uniformly distributing the filter-pack materials at a slow, even rate;
3) avoiding the use of quick-setting (high temperature) cements for thermoplastic casing installation;
4) adding sand or bentonite to a cement to lower the heat of hydration; and
5) controlling negative pressures inside the well during development.

Chemical Resistance Characteristics —

Materials used for well casing in monitoring wells must be durable enough to withstand galvanic or electrochemical corrosion and chemical degradation. Metallic casing materials are most subject to corrosion; thermoplastic casing materials are most subject to chemical degradation. The extent to which these processes occur depends on water quality within the formation and changing chemical conditions such as fluctuations between oxidizing and reducing states. Casing material must therefore be chosen with a knowledge of the existing or anticipated ground-water chemistry. When anticipated water quality is unknown, it is prudent to use conservative materials to avoid chemical or potential water quality problems. If ground-water chemistry affects the structural integrity of the casing, the products of casing deterioration may also adversely affect the chemistry of water samples taken from the wells.

Chemical Interference Characteristics —

Materials used for monitoring well casing must not exhibit a tendency to either sorb (take out of solution by either adsorption or absorption) or leach chemical constituents from or into the water that is sampled from the well. If a casing material sorbs selected constituents from the ground water, those constituents will either not be present in any water-quality sample (a "false negative") or the level of constituents will be reduced. Additionally, if ground-water chemistry changes over time, the chemical constituents that were previously sorbed onto the casing may begin to desorb and/or leach into the ground water. In either situation, the water-quality samples are not representative.

In the presence of aggressive aqueous solutions, chemical constituents can be leached from casing materials. If this occurs, chemical constituents that are not indicative of formation water quality may be detected in samples collected from the well. This "false positive" might be considered to be an indication of possible contamination when the constituents do not relate to ground-water contamination per se, but rather to water sample contamination contributed by the well casing material. The selection of a casing material must therefore consider potential interactions between the casing material and the natural and the man-induced geochemical environment. It is important to avoid "false positive" and especially "false negative" sample results.

Types of Casing Materials

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

1) fluoropolymer materials, including polytetrafluoroethylene(PTFE), tetrafluoroethylene (TFE), fluorinated ethylene propylene (FEP), perfluoroalkoxy (PFA) and polyvinylidene fluoride (PVDF);
2) metallic materials, including carbon steel, low-carbon steel, galvanized steel and stainless steel (304 and 316); and
3) thermoplastic materials, including polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS).

In addition to the three categories that are widely used, fiberglass-reinforced materials including fiberglass-reinforced epoxy (FRE) and fiberglass-reinforced plastic (FRP) have been used for monitoring applications. Because these materials have not yet been used in general application across the country, very little data are available on characteristics and performances. Therefore, fiberglass-reinforced materials are not considered further herein.

Each material possesses strength-related characteristics and chemical resistance/chemical interference characteristics that influence its use in site-specific hydrogeologic and contaminant-related monitoring situations. These characteristics for each of the three categories of materials are discussed below.

Fluoropolymer materials —

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

There exist a variety of fluoropolymer materials that are marketed under a number of different trademarks. Descriptions and basic physical properties of some of the more popular fluoropolymers with appropriate trademarks are discussed below.

Polytetrafluoroethylene (PTFE) was discovered by E.I. DuPont de Nemours in 1938 and was available only to the United States government until the end of World War II. According to Hamilton (1985), four principal physical properties are:

1) extreme temperature range -- from -400°F to +500°F in constant service;
2) outstanding electrical and thermal insulation;

3) lowest coefficient of friction of any solid material; and
4) almost completely chemically inert, except for some reaction with halogenated compounds at elevated temperatures and pressures.

In addition, PTFE is flexible without the addition of plasticizers and is fairly easily machined, molded or extruded. PTFE is by far the most widely-used and produced fluoropolymer. Trade names, manufacturers and countries of origin of PTFE and other fluoropolymer materials are listed in Table 24. Typical physical properties of the various fluoropolymer materials are described in Table 25.

Fluorinated ethylene propylene (FEP) was also developed by E.I. DuPont de Nemours and is perhaps the second most widely used fluoropolymer. It duplicates nearly all of the physical properties of PTFE except the upper temperature range, which is 100°F lower. Production of FEP-finished products is generally faster because FEP is melt-processible, but raw materials costs are higher.

Perfluoroalkoxy (PFA) combines the best properties of PTFE and FEP, but the former costs substantially more than either of the other fluoropolymers. Polyvinylidene fluoride (PVDF) is tougher and has a higher abrasion resistance than other fluoropolymers and is resistant to radioactive environments. PVDF has a lower upper temperature limit than either PTFE or PFA.

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

For construction of ground-water monitoring wells, fluoropolymers possess several advantages over other thermoplastics and metallic materials. For example, fluoropolymers are almost completely inert to chemical attack, even by extremely aggressive acids (i.e., hydrofluoric, nitric, sulfuric and

Table 24. Trade Names, Manufacturers, and Countries of Origin for Various Fluoropolymer Materials

Chemical Formulation	Trade Name	Manufacturer	Country of Origin
PTFE (or TFE)- Polytetrafluoroethylene	Teflon	DuPont	USA, Holland, Japan
	Halon	Allied	USA
	Fluon	ICI	UK, USA
	Hostaflon	Hoechs	W. Germany
	Polyflon	Daikin	Japan
	Algoflon	Montedison	Italy
	Soriflon	Ugine Kuhlman	France
FEP- Fluorinated ethylene propylene	Neoflon	Daikin	Japan
	Teflon	DuPont	USA, Japan, Holland
PFA- Perfluoroalkoxy	Neoflon	Daikin	Japan
	Teflon	DuPont	USA, Japan, Holland
PVDF- Polyvinylidene fluoride	Kynar	Pennwalt	USA
CTFE- Chlorotrifluoroethylene	Kel-F	3M	USA
	Diaflon	Daikin	Japan

Table 25. Typical Physical Properties of Various Fluoropolymer Materials (After Norton Performance Plastics, 1985)

Properties	Units	ASTM Method	TFE	FEP	PFA	E-CTFE	CTFE
Tensile strength @73°F	psi	D638-D651	2500-6000	2700-3100	4000-4300	7000	4500-6000
Elongation @73°F	%	D638	150-600	250-330	300-350	200	80-250
Modulus@ 73°F							
Tensile	psi	D638	45,000-115,000		-	240,000	206,000
Flexural	psi	D790	70,000-110,000	95,000	95,000-100,000	240,000	238,000
Elasticity in tension		D747	58,000	250,000	--	-	$1.5\text{-}3.0 \times 10^{6}$
Flexural strength@73°F	psi	D790	Does not break	Does not break	Does not break	7000	8500
Izod impact strength (1/2 X1/2-in. notched bar)							
@+75°F	ft. lbs./in. of notch	D256	3.0	No break	No break	No break	5.0
@-65°F	ft. lbs./in. of notch		2.3	2.9	-	-	-
Tensile impact strength							
@+73°F	ft. lbs./sq. in.	D1822	320	1020	-	-	-
@-65°F	ft. lbs./sq. in.		105	365	-	-	-
Compressive stress @ 73°F	psi	D695	1700	-	-	-	4600-7400
Specific gravity		D792	2.14-2.24	2.12-2.17	2.12-2.17	1.68	2.10-2.13
Coefficient of friction static & kinetic against polished steel			0.05-0.08	0.06-0.09	0.05-0.06	0.15-0.65	0.2-0.3
Coefficient of linear thermal-expansion	/°F	D696	5.5×10^{-5}	5.5×10^{-5}	6.7×10^{-5}	14×10^{-5}	2.64×10^{-5}

hydrochloric) and organic solvents. In addition, sorption of chemical constituents from solutions and leaching of materials from the fluoropolymer chemical structure has been believed be minimal or non-existent. Although studies are still ongoing, Reynolds and Gillham (1985) indicate that extruded tubing of at least one fluoropolymer (PTFE) is prone to absorption of selected organic compounds, specifically 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, hexachloroethane and tetrachloroethane; a fifth organic compound studied, bromoform, was not sorbed by PTFE. An observation of particular note made by Reynolds and Gillham was that tetrachloroethane was strongly and rapidly sorbed by the PTFE tubing such that significant reductions in concentration occurred within minutes of exposure to a solution containing the aforementioned organic compounds. These results indicate that PTFE may not be as inert as previously thought. Barcelona and Helfrich (1988) provide a review of laboratory and field studies of well casing material effects.

Although numerous such wells have been successfully installed, there may be some potential drawbacks to using fluoropolymers as monitoring well casing materials. For example, PTFE is approximately 10 times more expensive than PVC. In addition, fluoropolymer materials are more difficult to handle than most other well casing materials. Fluoropolymer materials are heavier and less rigid than other thermoplastics and slippery when wet because of a low coefficient of friction. Dablow et al. (1988) discuss installation of fluoropolymer wells and address some of the potential difficulties. As they point out, several strength-related properties of fluoropolymers (PTFE in particular) must be taken into consideration during the well design process, including: 1) pull-out resistance of flush-joint threaded couplings (tensile strength); 2) compressive strength of the intake section; and 3) flexibility of the casing string.

The tensile strength of fluoropolymer casing joints is the limiting factor affecting the length of casing that can be supported safely in a dry borehole. According to Dablow et al. (1988), experimental work conducted by DuPont indicates that PTFE threaded joints will resist a pull-out load of approximately 900 pounds. With a safety factor of two, 2-inch schedule 40 PTFE well casing with a weight of approximately 1.2 pounds per foot should be able to be installed to a depth of approximately 375 feet. Barcelona et al. (1985a) suggest that the recommended hang length not exceed 320 feet. In either case, this is less than one tenth the tensile strength of an equivalent-sized thermoplastic (i.e., PVC) well casing material. Additionally, because the specific gravity of PTFE is much higher than that of thermoplastics (about 2.2), the buoyant force of water is not great. However, the buoyant force is sufficient to increase the maximum string length by approximately 10 percent for that portion of the casing material in contact with water.

Compressive strength of fluoropolymer well casings and particularly intakes is also a recognized problem area. A low compressive stress when compared to other thermoplastics may lead to failure of the fluoropolymer casing at the threaded joints where the casing is weakest and the stress is greatest. According to Dablow et al. (1988), the "ductile" behavior of PTFE has resulted in the partial closing of intake openings with a consequent reduction in well efficiency in deep fluoropolymer wells. Dablow et al. (1988) suggest that this problem can be minimized by designing a larger slot size than is otherwise indicated by the sieve analyses. In compressive strength tests conducted by DuPont to determine the amount of deformation in PTFE well intakes that occurs under varying compressive stresses, a linear relationship was demonstrated between applied stress and the amount of intake deformation. This relationship is graphically presented in Figure 51. From this graph, the anticipated intake opening deformation can be determined and included in intake design by calculating the load and adding anticipated intake opening deformation to the intake opening size determined by sieve analysis.

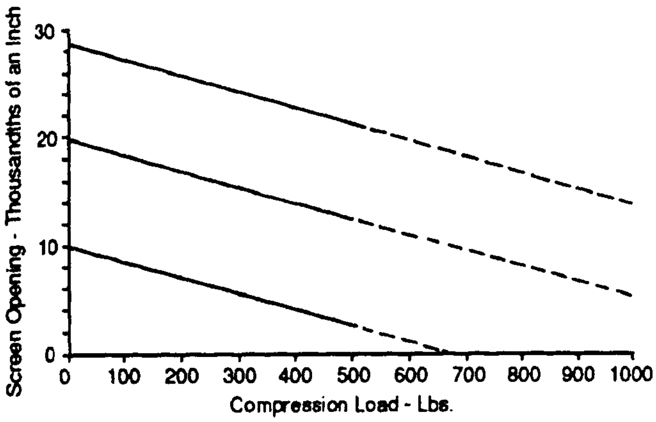


Figure 51. Static compression results of Teflon* screen (Dablow et al., 1988).
***Dupont's registered trademark for its fluorocarbon resin**

According to Dablow et al. (1988), a recommended construction procedure to minimize compressive stress problems is to keep the casing string suspended in the borehole so that the casing is in tension and to backfill the annulus around the casing while it remains suspended. This procedure reduces compressive stress by supplying support on the outer wall of the casing. This can only be accomplished successfully in relatively shallow wells in which the long-term tensile strength of the fluoropolymer casing is sufficient to withstand tensile stresses imposed on the casing by suspending it in the borehole. Additionally, continuous suspension of casing in the borehole is not possible with hollow-stem auger installations.

The third area of concern in fluoropolymer well casing installation is the extreme flexibility of the casing string. Although easy solutions exist to avoid problems, the flexibility otherwise could cause the casing to become bowed and non-plumb when loaded, and the resulting deformation could cause difficulties in obtaining samples or accurate water levels from these wells. Dablow et al. (1988) suggest three means of avoiding flexibility problems: 1) suspending the casing string in the borehole during backfilling (as discussed above); 2) using casing centralizers; or 3) inserting a rigid PVC or steel pipe temporarily inside the fluoropolymer casing during backfilling.

Metallic Materials —

Metallic well casing and screen materials available for use in monitoring wells include carbon steel, low carbon steel, galvanized steel and stainless steel. Well casings made of any of these metallic materials are generally stronger, more rigid and less temperature sensitive than thermoplastics, fluoropolymer or fiberglass-reinforced epoxy casing materials. Table 26 describes dimensions, hydraulic collapse pressure, burst pressure and unit weight of stainless steel casing. The strength and rigidity capabilities of metallic casing materials are sufficient to meet virtually any subsurface condition encountered in a ground-water monitoring situation. However, metallic materials are subject to corrosion during long-term exposure to certain subsurface geochemical environments.

Corrosion of metallic well casings and well intakes can both limit the useful life of the monitoring well installation and result in ground-water sample analytical bias. It is important, therefore, to select both casing and screen that are fabricated of corrosion-resistant materials.

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

1) general oxidation or "rusting" of the metallic surface, resulting in uniform destruction of the surface with occasional perforation in some areas;
2) selective corrosion (dezincification) or loss of one element of an alloy, leaving a structurally weakened material;
3) bi-metallic corrosion, caused by the creation of a galvanic cell at or near the juncture of two different metals;
4) pitting corrosion, or highly localized corrosion by pitting or perforation, with little loss of metal outside of these areas; and
5) stress corrosion, or corrosion induced in areas where the metal is highly stressed.

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

1) low pH -- if ground water pH is less than 7.0, water is acidic and corrosive conditions exist;
2) high dissolved oxygen content -- if dissolved oxygen content exceeds 2 milligrams per liter, corrosive water is indicated;
3) presence of hydrogen sulfide (H_2S) -- presence of H_2S in quantities as low as 1 milligram per liter can cause severe corrosion;
4) total dissolved solids (TDS) -- if TDS is greater than 1000 milligrams per liter, the electrical conductivity of the water is great enough to cause serious electrolytic corrosion;
5) carbon dioxide (CO) -- corrosion is likely if the CO_2 content of the water exceeds 50 milligrams per liter; and
6) chloride ion (Cl) content -- if Cl content exceeds 500 milligrams per liter, corrosion can be expected.

Combinations of any of these corrosive conditions generally increase the corrosive effect. However, no data presently exist on the expected life of steel well casing materials exposed to natural subsurface geochemical conditions.

Carbon steels were produced primarily to provide increased resistance to atmospheric corrosion. Achieving this

Table 26. Hydraulic Collapse and Burst Pressure and Unit Weight of Stainless Steel Well Casing (Dave Kill, Johnson Division, St. Paul, Minnesota, Personal Communication, 1985)

Nom. Size Inches	Schedule Number	Outside Diameter, Inches	Wall Thickness Inches	Inside Diameter Inches	Internal Cross-Sectional Area Sq. In.	Internal Pressure psi Test.	Internal Pressure psi Bursting	External Pressure psi Collapsing	Weight Pounds per Foot
2	5	2.375	0.065	2.245	3.958	820	4.105	896	1.619
	10	2.375	0.109	2.157	3.654	1.375	6.884	2.196	2.663
	40	2.375	0.154	2.067	3.356	1.945	9.726	3.526	3.087
	80	2.375	0.218	1.939	2.953	2.500	13.768	5.419	5.069
2 1/2	5	2.875	0.083	2.709	5.761	865	4.330	1.001	2.498
	10	2.875	0.120	2.635	5.450	1.250	6.260	1.905	3.564
	40	2.875	0.203	2.469	4.785	2.118	10.591	3.931	5.347
3	5	3.500	0.083	3.334	8.726	710	3.557	639	3.057
	10	3.500	0.120	3.260	8.343	1.030	5.142	1.375	4.372
	40	3.500	0.216	3.068	7.389	1.851	9.257	3.307	7.647
3 1/2	5	4.000	0.083	3.834	11.54	620	3.112	431	3.505
	10	4.000	0.120	3.760	11.10	900	4.500	1.081	5.019
	40	4.000	0.226	3.548	9.887	1.695	8.475	2.941	9.194
4	5	4.500	0.083	4.334	14.75	555	2.766	316	3.952
	10	4.500	0.120	4.260	14.25	800	4.000	845	5.666
	40	4.500	0.237	4.026	12.72	1.580	7.900	2.672	10.891
5	5	5.563	0.109	5.345	22.43	587	2.949	350	6.409
	10	5.563	0.134	5.295	22.01	722	3.613	665	7.842
	40	5.563	0.258	5.047	20.00	1.391	6.957	2.231	14.754
6	5	6.625	0.109	6.407	32.22	494	2.467	129	7.656
	10	6.625	0.134	6.357	31.72	606	3.033	394	9.376
	40	6.625	0.280	6.065	28.89	1.268	6.340	1.942	19.152

increased resistance requires that the material be subjected to alternately wet and dry conditions. In most monitoring wells, water fluctuations are not sufficient in either duration or occurrence to provide the conditions that minimize corrosion. Therefore, corrosion is a frequent problem. The difference between the corrosion resistance of carbon and low-carbon steels is negligible under conditions in which the materials are buried in soils or in the saturated zone; thus both materials may be expected to corrode approximately equally. Corrosion products include iron and manganese and trace metal oxides as well as various metal sulfides (Barcelona et al., 1983). Under oxidizing conditions, the principal products are solid hydrous metal oxides; under reducing conditions, high levels of dissolved metallic corrosion products can be expected (Barcelona et al., 1983). While the electroplating process of galvanizing improves the corrosion resistance of either carbon or low-carbon steel, in many subsurface environments the improvement is only slight and short-term. The products of corrosion of galvanized steel include iron, manganese, zinc and trace cadmium species (Barcelona et al., 1983).

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

Conversely, stainless steel performs well in most corrosive environments, particularly under oxidizing conditions. In fact, stainless steel requires exposure to oxygen in order to attain its highest corrosion resistance; oxygen combines with part of the stainless steel alloy to form an invisible protective film on the surface of the metal. As long as the film remains intact, the corrosion resistance of stainless steel is very high. Recent work by Barcelona and Helfrich (1986; 1988) and Barcelona et al. (1988) suggest that biological activity may alter geochemistry near stainless steel wells. Iron bacteria may induce degradation of the well casing and screen.

Several different types of stainless steel alloys are available. The most common alloys used for well casing and screen are Type 304 and Type 316. Type 304 stainless steel is perhaps the most practical from a corrosion resistance and cost standpoint. It is composed of slightly more than 18 percent chromium and more than 8 percent nickel, with about 72 percent iron and not more than 0.08 percent carbon (Driscoll, 1986). The chromium and nickel give the 304 alloy excellent resistance to corrosion; the low carbon content improves weldability. Type 316 stainless steel is compositionally similar to Type 304 with one exception -- a 2 to 3 percent molybdenum content and a higher nickel content that replaces the equivalent percentage of iron. This compositional difference provides Type 316 stainless steel with an improved resistance to sulfur-containing species as well as sulfuric acid solutions (Barcelona et al., 1983). This means that Type 316 performs better under reducing conditions than Type 304. According to Barcelona et al. (1983), Type 316 stainless steel is less susceptible to pitting or pinhole corrosion caused by organic acids or halide solutions. However, Barcelona et al. (1983) also point out that for either formulation of stainless steel, long-term exposure to very corrosive conditions may result in corrosion and the subsequent chromium or nickel contamination of samples.

Thermoplastic Materials —

Thermoplastics are man-made materials that are composed of different formulations of large organic molecules. These formulations soften by heating and harden upon cooling and therefore can easily be molded or extruded into a wide variety of useful shapes including well casings, fittings and accessories.

The most common types of thermoplastic well casing are polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS). Casing made of these materials is generally weaker, less rigid and more temperature-sensitive than metallic casing materials. However, casing made of either types of plastic can usually be selected where the strength, rigidity and temperature resistance are generally sufficient to withstand stresses during casing handling, installation and earth loading (National Water Well Association and Plastic Pipe Institute, 1981). Thermoplastics also: 1) offer complete resistance to galvanic and electrochemical corrosion; 2) are light weight for ease of installation and reduced shipping costs; 3) have high abrasion resistance; 4) have high strength-to-weight ratios; 5) are durable in natural ground-water environments; 6) require low maintenance; 7) are flexible and workable for ease of cutting and joining and 8) are relatively low in cost.

Long-term exposures of some formulations of thermoplastics to the ultraviolet rays of direct sunlight and/or to low temperatures will cause brittleness and gradual loss of impact strength that may be significant. The extent of this degradation depends on the type of plastic, the extent of exposure and the susceptibility of the casing to mechanical damage (National Water Well Association and Plastic Pipe Institute, 1981). Many thermoplastic formulations now include protection against degradation by sunlight, but brittleness of casing, particularly during casing installation remains a problem. Above-ground portions of thermoplastic well casings should be suitably protected from breakage. Potential chemical problems are discussed in the following sections.

Polyvinyl chloride (PVC)—PVC plastics are produced by combining PVC resin with various types of stabilizers, lubricants, pigments, fillers, plasticizers and processing aids. The amounts of these additives can be varied to produce different PVC plastics with properties tailored to specific applications. PVC used for well casing is composed of a rigid unplasticized polymer formulation (PVC Type 1) that is strong and generally has good chemical resistance. However, several publications (e.g., Barcelona et al., 1983; Barcelona and Helfrich, 1988; and Nass, 1976) raised questions of chemical resistance to low molecular weight ketones, aldehydes and chlorinated solvents which may limit durability of the casing.

PVC materials are classified according to ASTM standard specification D-1785 that covers rigid PVC compounds (American Society for Testing and Materials, 1986). This standard categorizes rigid PVC by numbered cells designating value ranges for certain pertinent properties and characteristics including impact strength, tensile strength, rigidity (modulus of elasticity), temperature resistance (deflection temperature) and chemical resistance. ASTM standard specification F-480 covers thermoplastic water well casing pipe and couplings made in standard dimension ratios. This standard specifies that PVC well casing can be made from only a limited number of cell classification materials, predominantly PVC 12454-B, but also including PVC 12454-C and PVC 14333-C and D (American Society for Testing and Materials, 1981). Minimum physical property values for these materials are given in Table 27. Hydraulic collapse pressure and unit weight for a range of PVC well casing diameters is given in Table 28.

Acrylonitrile butadiene styrene (ABS)--ABS plastics are produced from three different monomers: 1) acrylonitrile, 2) butadiene and 3) styrene. The ratio of the components and the way in which they are combined can be varied to produce plastics with a wide range of properties. Acrylonitrile contributes rigidity, impact strength, hardness, chemical resistance and heat resistance; butadiene contributes impact strength; styrene contributes rigidity, gloss and ease of manufacturing (National Water Well Association arid Plastic Pipe Institute, 19181). ABS used for well casing is a rigid, strong unplasticized polymer formulation that has good heat resistance and impact strength.

Two ABS material types are used for well casings: 1) a higher strength, high rigidity, moderate impact resistance ABS and 2) a lower strength and rigidity, high impact strength ABS. These two materials are identified as cell class 434 and 533, respectively by ASTM standard specification F-480 (American Society for Testing and Materials, 1981). Minimum physical property values for ABS well casing are given in Table 27. The high temperature resistance and the ability of ABS to retain other properties better at high temperatures is an advantage in wells in which grouting causes a high heat of hydration. Hydraulic collapse pressure for a range of ABS well casing diameters is given in Table 29.

General strength/chemical resistance and/or interference characteristics--The tensile strength of thermoplastics is relatively low in comparison to metallic materials, but the developed string loading is not a limiting factor because the thermoplastic well casing is lighter weight than metallic materials. Table 27 shows the physical properties of thermoplastic well casing materials. The tensile strength, which in part determines the length of casing string that can be suspended in the borehole is relatively large. According to calculations by the National Water Well Association and Plastic Pipe Institute (1981), permissible casing string lengths even in unsaturated boreholes exceed the typical borehole depths of monitoring wells. In boreholes where the casing is partially immersed, casing string length is even less of a problem because the thermoplastics are low in density and therefore relatively buoyant.

With respect to chemical resistance, thermoplastic well casing materials are non-conductors and therefore do not corrode either electrochemically or galvanically like metallic materials. In addition, thermoplastics are resistant to biological attack and to chemical attack by soil, water and other naturally-occurring substances present in the subsurface (National Water Well Association and Plastic Pipe Institute, 1981). However, thermoplastics are susceptible to chemical attack by high concentrations of certain organic solvents, and long term exposure to lower levels has as yet undocumented effects. This physical degradation of a plastic by an organic solvent is called solvation. Solvent cementing of thermoplastic well casings is based on solvation. Solvation occurs in the presence of very high concentrations of specific organic solvents. If these solvents, which include tetrahydrofuran (THF), methyl ethyl ketone (MEK), methyl isobutyl ketone (MIBK) and cyclohexanone, are present in high enough concentrations, the solvents can be expected to chemically degrade thermoplastic well casing. However, the extent of this degradation is not known. In general, the chemical attack on the thermoplastic polymer matrix is enhanced as the organic content of the solution with which it is in contact increases.

Barcelona et al. (1983) and the Science Advisory Board of the U.S. EPA list the groups of chemical compounds that may cause degradation of the thermoplastic polymer matrix and/or the release of compounding ingredients that otherwise will remain in the solid material. These chemical compounds include: 1) low molecular weight ketones, 2) aldehydes, 3) amines and 4) chlorinated alkenes and alkanes. Recent reports of creosotes and petroleum distillates causing disintegration of PVC casing support Barcelona's findings. There is currently a lack of information regarding critical concentrations of these chemical compounds at which deterioration of the thermoplastic material is significant enough to affect either the structural integrity of the material or the ground-water sample chemical quality.

Among the potential sources of chemical interference in thermoplastic well casing materials are the basic monomers from which the casing is made and a variety of additives that may be used in the manufacture of the casing including plasticizers, stabilizers, fillers, pigments and lubricants. The propensity of currently available information on potential contamination of water that comes in contact with rigid thermoplastic materials relates specifically to PVC; no information is currently available on ABS or on other similar thermoplastics. Therefore, the remainder of this discussion relates to potential chemical interference effects from PVC well casing materials.

Extensive research has been conducted in the laboratory and in the field, specifically on water supply piping, to evaluate vinyl chloride monomer migration from new and old PVC pipe. The data support the conclusion that when PVC is in contact with water, the level of trace vinyl chloride migration from PVC pipe is extremely low compared to residual vinyl chloride monomer (RVCM) in PVC pipe. Since 1976, when the National Sanitation Foundation established an RVCM monitoring and control program for PVC pipe used in potable water supplies and well casing, process control of RVCM levels in PVC pipe has improved markedly. According to Barcelona et al. (1983), the maximum allowable level of RVCM in NSF-certified PVC products (less than or equal to 10 ppm RVCM) limits potential leached concentrations of vinyl chloride monomer to 1 to 2 micrograms per liter. Leachable amounts of vinyl chloride monomer should decrease as RVCM levels in products continue to be reduced. Although the potential for analytical interference exists even at the low micrograms per-liter level at which vinyl

Table 27. Typical Physical Properties of Thermoplastic Well Casing Materials at 73.4° (National Water Well Association and Plastic Pipe Institute, 1981)

Property	ASTM Test Method	434 (Cell Class, per D-1788)	533	12454-B & C (PVC Cell Class, per D-1784)	14333-C & D
Specific Gravity	D-792	1.05	1.04	1.40	1.35
Tensile Strength, lbs. /in.^{2}	D-638	6,000*	5,000*	7,000*	6,000*
Tensile Modulus of Elasticity, lbs./in.^{2}	D-638	350,000	250,000	400,000*	320,000*
Compressive Strength, lbs./in.^{2}	D-695	7,200	4,500	9,000	8,000
Impact Strength, Izod, ft. -lb/inch notch	D-256	4.0*	6.0*	0.65	5.0
Deflection Temperature Under Load (264 psi), °F	D-648	190*	190*	158*	140*
Coefficent of Linear Expansion, in./in. - °F	D-696	5.5 X10^{-5}	6.0 X 10^{-5}	3.0 X10^{-5}	5.0 X10^{-5}

* These are minimum values set by the corresponding ASTM Cell Class designation. All others represent typical values.

Table 28. Hydraulic Collapse Pressure and Unit Weight of PVC Well Casing (National Water Well Association and Plastic Pipe Institute, 1981)

Outside Diameter (Inches) Nom.	Actual	SCH*	Wall Thickness Min. (in.)	DR**	Weight in Air (lbs/100 feet) PVC 12454	PVC14333	Weight in Water (lbs/100 feet) PVC 12454	PVC 14333	Hydraulic Collapse Pressure (psi) PVC 12454	PVC 14333
2	2.375	SCH 80	0.218	10.9	94	91	27	24	947	758
		SCH 40	0.154	15.4	69	66	20	17	307	246
2 1/2	2.875	SCH 80	0.276	10.4	144	139	41	36	1110	885
		SCH 40	0.203	14.2	109	105	31	27	400	320
3	3.500	SCH 80	0.300	11.7	193	186	55	48	750	600
		SCH 40	0.216	16.2	143	138	41	36	262	210
3 1/2	4.000	SCH 80	0.316	12.6	235	227	67	59	589	471
		SCH 40	0.226	17.7	172	176	49	43	197	158
4	4.500	SCH 80	0.337	13.3	282	272	80	70	494	395
		SCH 40	0.237	19.0	203	196	58	51	158	126
4 1/2	4.950	-	0.248	20.0	235	226	67	58	134	107
		-	0.190	26.0	182	176	52	46	59	47
5	5.563	SCH 80	0.375	14.5	391	377	112	98	350	280
		SCH 40	0.258	21.6	276	266	79	69	105	84
6	6.625	SCH 80	0.432	15.3	538	519	154	134	314	171
		SCH 40	0.280	23.7	358	345	102	89	78	62

* Schedule

Table 29. Hydraulic Collapse Pressure and Unit Weight of ABS Well Casing (National Water Well Association and Plastic Pipe Institute, 1981)

Outside Diameter (Inches) Nom.	Actual	SCH*	Wall Thickness Min. (in.)	DR**	Weight in Air (lbs/100 feet) ABS 434	ABS 533	Weight in Water (lbs/100 feet) ABS 434	ABS 533	Hydraulic Collapse Pressure (psi) ABS 434	ABS 533
2	2.375	SCH 80	0.218	10.9	71	70	3.4	2.7	829	592
		SCH 40	0.154	15.4	52	51	2.5	2.0	269	192
2 1/2	2.875	SCH 80	0.276	10.4	108	107	5.1	4.1	968	691
		SCH 40	0.203	14.2	82	81	3.9	3.1	350	250
3	3.500	SCH 80	0.300	11.7	145	144	6.9	5.5	656	468
		SCH 40	0.216	16.2	107	106	5.1	4.1	229	164
3 1/2	4.000	SCH 80	0.318	12.6	176	175	8.4	6.7	515	368
		SCH 40	0.226	17.7	129	128	6.1	4.9	173	124
4	4.500	SCH 80	0.337	13.3	211	209	10.0	8.0	432	308
		SCH 40	0.237	19.0	152	151	7.2	5.8	138	98
5	5.563	SCH 80	0.375	14.8	294	291	14.0	11.2	306	218
		SCH 40	0.258	21.6	207	205	9.8	7.9	92	66
6	6.250	SCH 80	0.432	15.3	404	400	19.2	15.4	275	196
		SCH 40	0.280	23.7	268	266	12.8	10.2	69	49

chloride monomer may be found in a solution in contact with PVC, the significance of this interference is not currently known.

With few exceptions, plasticizers are not added to PVC formulations used for well casing because the casing must be a rigid material. Even if plasticizers were added, levels would not be expected to exceed 0.01 percent (Barcelona et al., 1983). By contrast, flexible PVC tubing may contain from 30 to 50 percent plasticizers by weight. The presence of these high levels of plasticizers in flexible PVC tubing has been documented to produce significant chemical interference effects by several researchers (Barcelona et al., 1985b; Barcelona, 1984; Barcelona et al., 1983; Junk et al., 1974). However, at the levels present in rigid well casing, plasticizers were not reported to pose a chemical interference problem.

Rigid PVC may contain other additives, primarily stabilizers, at levels approaching 5 percent by weight. Some representative chemical classes of additives that have been used in the manufacture of rigid PVC well casing are listed in Table 30. Boettner et al. (1981) determined through a laboratory study that several of the PVC heat stabilizing compounds, notably dimethyltin and dibutyltin species, could potentially leach out of rigid PVC at very low (low to sub micrograms per liter) levels. These levels decreased dramatically over time. Factors that influenced the leaching process in this study included solution pH, temperature and ionic composition; and exposed surface area and surface porosity of the pipe material. It is currently unclear what impact, if any, the leaching of low levels of organotin compounds may have on analytical interference.

In addition to setting a limit on RVCM, the National Sanitation Foundation has set specifications for certain chemical constituents in PVC formulations. The purpose of these specifications as outlined in NSF Standard 14 (National Sanitation Foundation, 1988) is to control the amount of chemical additives in both PVC well casing and pipe used for potable water supply. The maximum contaminant levels permitted in a standardized leach test on NSF-approved PVC products are given in Table 31. Most of these levels correspond to those set by the Safe Drinking Water Act for chemical constituents covered by the National Interim Primary Drinking Water Standards. Only PVC products that carry either the "NSF wc" (well casing) or "NSF pw" (potable water) designation have met the specifications set forth in Standard 14. Other non-NSF listed products may include in their formulation chemical additives not addressed by the specifications or may carry levels of the listed chemical parameters higher than permitted by the specifications. In all cases, the material used should be demonstrated to be compatible with the specific applications. For example, even though neither lead nor cadmium have been permitted as compounding ingredients in United States-manufactured NSF-listed PVC well casing since 1970, PVC manufactured in other countries may be stabilized with lead or cadmium compounds that have been demonstrated to leach from the PVC (Barcelona et al., 1983).

In other laboratory studies of leaching of PVC well casing material chemical components into water, Curran and Tomson (1983) and Parker and Jenkins (1986) determined that little or no leaching occurred. In the former study, it was found when testing several different samples (brands) of rigid PVC well casing that trace organics either were not leached or were leached only at the sub-micrograms per liter level. In the latter study, which was conducted using ground water in contact with two different brands of PVC, it was concluded that no chemical constituents were leached at sufficient concentrations to interfere with reversed-phase analysis for low micrograms per liter levels of 2,4,6 trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) or 2,4 dinitrotoluene (DNT) in solution. The study by Curran and Tomson (1983) confirmed previous field work at Rice University (Tomson et al., 1979) that suggested that PVC well casings did not leach significant amounts (i.e. at the sub-micrograms per liter level) of trace organics into sampled ground water.

Another potential area for concern with respect to chemical interference effects is the possibility that some chemical constituents could be sorbed by PVC well casing materials. Miller (1982) conducted a laboratory study to determine whether several plastics, including rigid PVC well casing, exhibited any tendency to sorb potential contaminants from solution. Under the conditions of his test, Miller found that PVC moderately sorbed tetrachloroethylene and strongly sorbed lead, but did not sorb trichlorofluoromethane, trichloroethylene, bromoform, 1,1,1-trichloroethane, 1,1,2-trichloroethane or chromium. In this experiment, sorption was measured weekly for six weeks and compared to a control; maximum sorption of tetrachloroethylene occurred at two weeks. While Miller (1982) attributed these losses of tetrachloroethylene and lead strictly to sorption, the anomalous behavior of tetrachloroethylene compared to that for other organics of similar structure (i.e., trichloroethlyene) is not explained. In a follow-up study to determine whether or not the tetrachloroethylene could be desorbed and recovered, only a small amount of tetrachloroethylene was desorbed. Thus, whether or not strong sorption or some other mechanism (i.e., enhanced biodegradation in the presence of PVC) accounts for the difference is not clear (Parker and Jenkins, 1986). In the laboratory study by Parker and Jenkins (1986), it was found that significant losses of TNT and HMX from solution occurred in the presence of PVC well casing. A follow-up study to determine the mechanism for the losses attributed the losses to increased microbial degradation rather than to sorption. These results raise questions regarding whether or not losses found in other laboratory or even field studies that did not consider biodegradation as a loss mechanism could be attributed to biodegradation rather than to sorption.

In another laboratory study, Reynolds and Gillham (1985) found that sorption of selected organics (specifically 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, bromoform, hexachloroethane and tetrachloroethylene) onto PVC and other polymeric well casing materials could be a significant source of bias to ground-water samples collected from water standing in the well. PVC was found to slowly sorb four of the five compounds studied (all except 1,1,1-trichloroethane), such that sorption bias would likely not be significant for the sorbed compounds if well development (purging the well of stagnant water) and sampling were to take place in the same day.

It is clear that with few exceptions the work that has been done to determine chemical interference effects of PVC well casing (whether by leaching from or sorbing to PVC of chemical constituents) has been conducted under laboratory conditions. Furthermore, in most of the laboratory work the PVC has been exposed to a solution (usually distilled, deionized, or "organic-free" water) over periods of time ranging from several days to several months. Thus the PVC had a period of time in which to exhibit sorption or leaching effects. While this may be comparable to a field situation in which ground water was exposed to the PVC well casing as it may be between sampling rounds, few studies consider the fact that prior to sampling, the well casing is usually purged of stagnant water residing in the casing between sampling rounds. Thus, the water that would have been affected by the sorption or leaching effects of PVC would ideally have been removed and replaced with aquifer-quality water that is eventually obtained as "representative" of existing ground-water conditions. Because the sample is generally taken immediately after purging of stagnant water, the sampled water will have had a minimum of time with which to come in contact with casing materials and consequently be affected by sorption or leaching effects. Because of this, Barcelona et al. (1983) suggest that the potential sample bias due to sorptive interactions with well casing materials may be discounted. They point out that these effects are far more critical in sample transfer and storage procedures employed prior to sample separation or analysis. Nevertheless, other researchers do not agree that purging avoids casing effects especially for wells that recover slowly and thereby allow ample time for surface reactions to occur.

Composite Alternative Materials —

In certain conditions it may be advantageous to design a well using more than one material for well components. For example, where stainless steel or fluoropolymer materials are preferred in a specific chemical environment, considerable cost savings may be realized by using PVC in non-critical portions of the well. These savings may be considerable especially in deep wells where only the lower portion of the well has a critical chemical environment and tens of feet of lower-cost PVC may be used in the upper portion of the well. In composite well designs the use of dissimilar metallic components should be avoided unless an electrically isolating design is incorporated (United States Environmental Protection Agency, 1986).

Coupling Procedures for Joining Casing

Only a limited number of methods are available for joining lengths of casing or casing and screen together. The joining method depends on the type of casing and type of casing joint. Figure 52 illustrates some common types of joints used for

Table 30. Representative Classes of Additives in Rigid PVC Materials Used for Pipe or Well Casing (Barcelona et al., 1983)

(Concentration in wt. %)

Heat stabilizers (0.2-1.0%)	**Fillers (1-5%)**
Dibutyltin diesters of lauric and maleic acids	$CaCO_3$
Dibutyltin bis (laurylmercaptide)	diatomaceous earth
Dibutyltin-ß mercaptopropionate	clays
di-n-octyltin maleate	pigments
-n-octyltin-S,S'-bis isoctyl mercaptoacetate	TiO_2
-n-octyltin-ß mercaptopropionate	carbon black
Various other alkyltin compounds	iron and other metallic oxides
Various proprietary antimony compounds	
	Lubricants (1-5%)
	stearic acid
	calcium stearate
	glycerol monostearate
	montan wax
	polyethylene wax

Table 31. Chemical Parameters Covered by NSF Standard 14 (National Sanitation Foundation, 1988)

Parameter	Maximum Permissible Level mg/L (ppm)
Antimony (Sb)	0.050
Arsenic (As)	0.050[1]
Barium(Ba)	1.0[1]
Cadmium (Cd)	0.010[1]
Chromium (Cr)	0.050[1]
Lead(Pb)	0.020[1]
Mercury (Hg)	0.0020[1]
Phenolic substances	0.050
Residual vinyl chloride monomer (RVCM)	2.0
Selenium (Se)	0.010[1]
Total dissolved solids	70.0
Tin (Sn)	0.050
Total trihalomethanes (TTHM)	0.10
Taste and Odor Evaluations	
Characteristic	Permissible Level
Odor	Cold application 40 Hot application 50
Taste	Satisfactory

.stablished in the U.S. EPA National Primary Drinking Water Regulations.
in the finished product ppm (mg/kg).

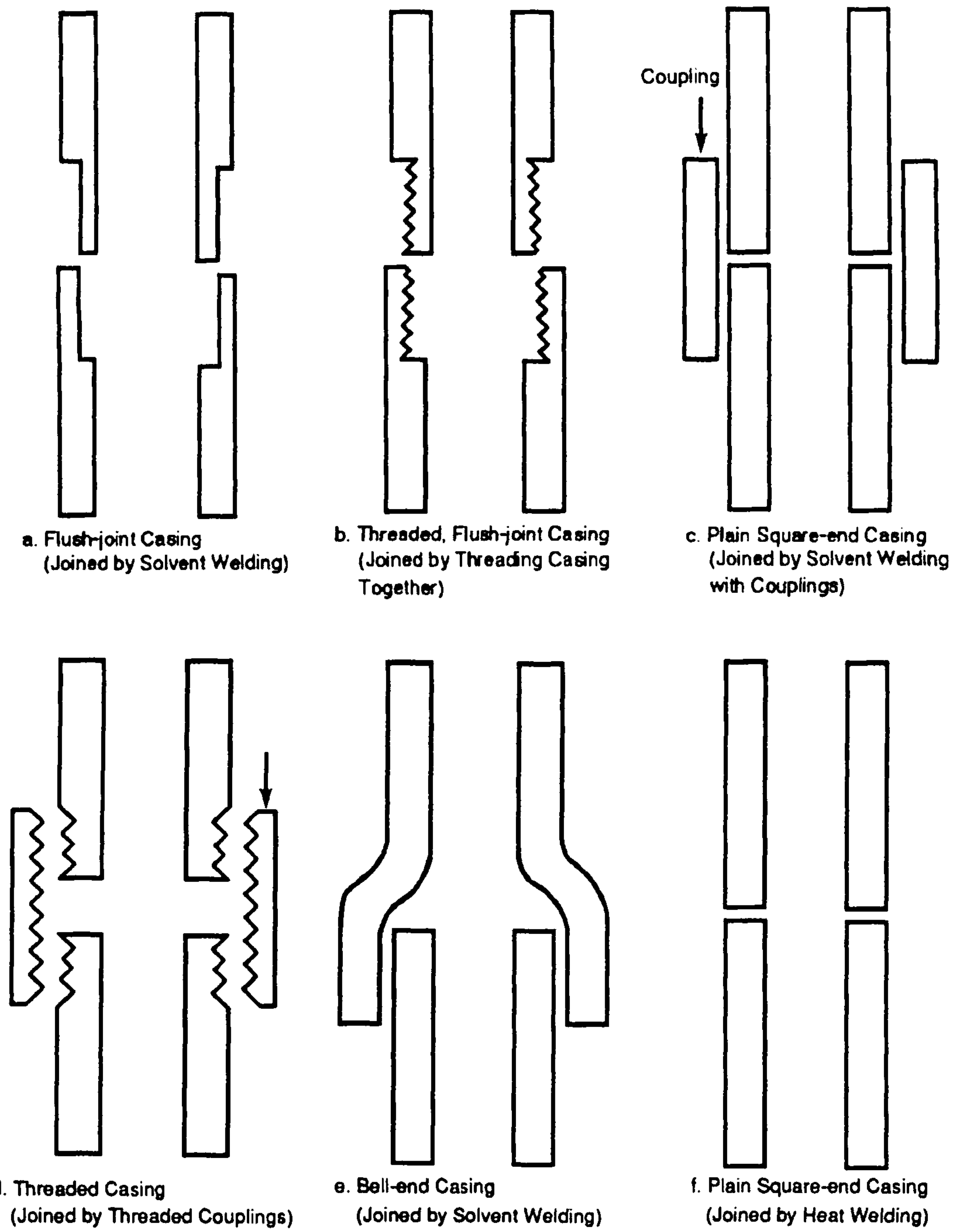


Figure 52. Types of joints typically used between casing lengths.

assembling lengths of casing. Flush-joint, threaded flush-joint, plain square-end and bell-end casing joints are typical of joints available for plastic casing; threaded flush-joint, bell-end and plain square end casing joints are typical of joints available for metallic casing.

Fluoropolymer Casing Joining —

Because fluoropolymers are inert to chemical attack or solvation even by pure solvents, solvent welding cannot be used with fluoropolymers. Similar to thermoplastic casing joining techniques, threaded joints wrapped with fluoropolymer tape are preferred.

Metallic Casing Joining —

There are generally two options available for joining metallic well casings: 1) welding via application of heat or 2) threaded joints. Both methods produce a casing string with a relatively smooth inner and outer diameter. With welding, it is generally possible to produce joints that are as strong or stronger than the casing, thereby enhancing the tensile strength of the casing string. The disadvantages of welding include: 1) greater assembly time, 2) difficulty in properly welding casing in the vertical position, 3) enhancement of corrosion potential in the vicinity of the weld and 4) the danger of ignition of potentially explosive gases that may be present. Because of these disadvantages, threaded joints are more commonly used with metallic casing and screen. Threaded joints provide inexpensive, fast and convenient connections and greatly reduce potential problems with chemical resistance or interference (due to corrosion) and explosive potential. Wrapping the male threads with fluoropolymer tape prior to joining sections improves the watertightness of the joint. One disadvantage to using threaded joints is that the tensile strength of the casing string is reduced to approximately 70 percent of the casing strength. This reduction in strength does not usually pose a problem because strength requirements for small diameter wells typical of monitoring installations are not as critical and because metallic casing has a high initial tensile strength.

Thermoplastic Casing Joining —

There are two basic methods for joining sections of thermoplastic well casing: 1) solvent cementing and 2) mechanical joining. Both methods should maintain a uniform inner and outer casing diameter in monitoring well installations. An inconsistent inner diameter causes problems when tight-fitting downhole equipment (development tools, sampling or purging devices, etc.) is used; an uneven outer diameter creates problems with filter pack and annular seal placement. The latter problem tends to promote water migration at the casing/seal interface to a greater degree than is experienced with uniform outerdiameter casing (Morrison, 1984).

Solvent cementing--In solvent cementing, a solvent primer is generally used to clean the two pieces of casing to be joined and a solvent cement is then spread over the cleaned surface areas. The two sections are assembled while the cement is wet. This allows the active solvent agent(s) to penetrate and soften the two casing surfaces that are joined. As the cement cures, the two pieces of casing are fused together; a residue of chemicals from the solvent cement remains at the joint. There are many different formulations of solvent cement for thermoplastics, but most cements consist of two or more of the following organic chemical constituents: tetrahydrofuran (THF), methyl ethyl ketone (MEK), methyl isobutyl ketone (MIBK), cyclohexanone and dimethylformamide (Sosebee et al., 1983).

The cements used in solvent welding, which are themselves organic chemicals, can have an impact on the integrity of ground-water samples. Sosebee et al. (1983) demonstrated that the aforementioned volatile organic solvents do contaminate ground-water samples collected from monitoring wells in which PVC adhesives are used to join well casing sections. Barcelona et al. (1983) noted that even minimal solvent cement application is sufficient to supply consistent levels of primer/cement components above 100 micrograms per liter in ground-water samples despite proper well development and flushing prior to sampling. They further point out that these effects may persist for months after well construction and even after repeated attempts to develop the wells. Dunbar et al. (1985) cited a case in which THF was found at levels ranging from 10 to 200 milligrams per liter in samples taken from several PVC-cased monitoring wells in which PVC solvent cement was used. These levels were found more than two years after the casing was installed. In samples from adjacent monitoring wells in which threaded PVC casing was used, no THF was found, prompting the conclusion that the THF concentrations were a relict of solvent cement used during well construction. The results of these studies point out that solvent cementing is not appropriate for use in joining sections of thermoplastic casing used in ground-water monitoring wells.

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

Because all joints in a monitoring well casing must be watertight, the extent of tightening of joints should comply with recommendations by the manufacturer. Overtightening of casing joints can lead to structural failure of the joint (National Water Well Association and Plastic Pipe Institute, 1981).

When using thermoplastic well casing, threaded joints are preferred; any problems associated with the use of solvent primers and cements can thus be avoided. Casing with threads machined or molded directly onto the pipe (without use of larger-diameter couplings) provides a flush joint between both inner and outer diameters. Because the annular space is frequently only minimal, casings that do not use couplings are best suited to use in monitoring well construction. Although this type of joint reduces the tensile strength of the casing string by about 30 percent as compared to a solvent-cemented joint, in most monitoring well installations this is not a critical concern. Where threaded joints are used, fluoropolymer tape is often wrapped around the threads prior to joining male and female sections to maximize the watertightness of the joint.

Well Casing Diameter

While casing outside diameters are standardized, variations in wall thickness cause casing inside diameters to vary. In "scheduled" casing, wall thickness increases as the scheduling number increases for any given diameter of casings. As illustrated by Figure 53, nominal 2-inch casing is a standard 2.375 inches outside diameter; wall thicknesses vary from 0.065 inch for schedule 5 to 0.218 inch for schedule 80. This means that inside diameters for nominal 2-inch casing vary from 2.245 inches for schedule 5 thin-walled casing (typical of stainless steel) to only 1.939 inches for schedule 80 thick-walled casing (typical of PVC). Wall thickness also changes with pipe diameter in scheduling. Another method of evaluating casing strength is by standard dimension ratios (SDR). A SDR is the ratio of the wall thickness to the casing diameter. The ratio is referenced to an internal pounds per square inch (psi) pressure rating such that all casings with a similar SDR will have a similar psi rating. Where strength of casing is important, scheduling and SDR numbers provide a means for choosing casing.

Although the diameter of the casing for a monitoring well depends on the purpose of the well, the casing size is generally selected to accommodate downhole equipment. Additional casing diameter selection criteria include: 1) drilling or well installation method used, 2) anticipated depth of the well and associated strength requirements, 3) ease of well development, 4) volume of water required to be purged prior to sampling (Table 32), 5) rate of recovery of the well after purging and 6)

Tabe 32. Volume of Water In Casing or Borehole (Driscoll, 1986)

Diameter of Casing or Hole (In)	Gallons per foot of Depth	Cubic Feet per Foot of Depth	Liters per Meter of Depth	Cubic Meters per Meter of Depth
1	0.041	0.0055	0.509	0.509 x 10^{-3}
1 1/2	0.092	0.0123	1.142	1.142 x 10^{-3}
2	0.163	0.0218	2.024	2.024 x 10^{-3}
2 1/2	0.255	0.0341	3.167	3.167 x 10^{-3}
3	0.367	0.0491	4.558	4.558 x 10^{-3}
3 1/2	0.500	0.0668	6.209	6.209 x 10^{-3}
4	0.653	0.0873	8.110	8.110 x 10^{-3}
4 1/2	0.826	0.1104	10.26	10.26 x 10^{-3}
5	1.020	0.1364	12.67	12.67 x 10^{-3}
5 1/2	1.234	0.1650	15.33	15.33 x 10^{-3}
6	1.469	0.1963	18.24	18.24 x 10^{-3}
7	2.000	0.2673	24.84	24.84 x 10^{-3}
8	2.611	0.3491	32.43	32.43 x 10^{-3}
9	3.305	0.4418	41.04	41.04 x 10^{-3}
10	4.080	0.5454	50.67	50.67 x 10^{-3}
11	4.937	0.6600	61.31	61.31 x 10^{-3}
12	5.875	0.7854	72.96	72.96 x 10^{-3}
14	8.000	1.069	99.35	99.35 x 10^{-3}
16	10.44	1.396	129.65	129.65 x 10^{-3}
18	13.22	1.767	164.18	164.18 x 10^{-3}
20	16.32	2.182	202.68	202.68 x 10^{-3}
22	19.75	2.640	245.28	245.28 x 10^{-3}
24	23.50	3.142	291.85	291.85 x 10^{-3}
26	27.58	3.687	342.52	342.52 x 10^{-3}
28	32.00	4.276	397.41	397.41 x 10^{-3}
30	36.72	4.909	456.02	456.02 x 10^{-3}
32	41.78	5.585	518.87	518.87 x 10^{-3}
34	47.16	6.305	585.68	585.68 x 10^{-3}
36	52.88	7.069	656.72	656.72 x 10^{-3}

1 Gallon = .785 Liters
1 Meter = 3.281 Feet
1 Gallon Water Weighs 8.33 lbs. = 3.785 Kilograms
1 Liter Water Weighs 1 Kilogram = 2.205 lbs.
1 Gallon per foot of depth = 12.419 liters per foot of depth
1 Gallon per meter of depth = 12.419 x 10^{-3} cubic meters per meter of depth

cost. For an additional discussion of casing diameter, refer to the sections entitled "Equipment that the Well Must Accommodate" and "Description and Selection of Drilling Methods."

Casing Cleaning Requirements

During the production of any casing material, chemical substances are used to assist in the extrusion, molding, machining and/or stabilization of the casing material. For example, oils and solvents are used in many phases of steel casing production. In the manufacturing of PVC well casing, a wax layer can develop on the inner wall of the casing; additionally, protective coatings of natural or synthetic waxes, fatty acids or fatty acid esters may be added to enhance the durability of the casing (Barcelona et al., 1983). These substances are potential sources of chemical interference and therefore must be removed prior to installation of the casing in the borehole. If trace amounts of these materials still adhere to the casing after installation, the chemical integrity of samples taken from the monitoring well can be affected.

Careful pre-installation cleaning of casing materials must be conducted to avoid potential chemical interference problems from the presence of substances such as cutting oils, cleaning solvents, lubricants, threading compounds, waxes and/or other chemical residues. For PVC, Curran and Tomson (1983) suggest washing the casing with a strong detergent solution and then rinsing with water before installation. Barcelona et al. (1983) and Barcelona (1984) suggest this same procedure for all casing materials. To accomplish the removal of some cutting oils, lubricants or solvents, it may be necessary to steam-clean casing materials or employ a high-pressure hot water wash. Casing materials must also be protected from contamination while they are on-site awaiting installation in the borehole. This can be accomplished by providing a clean storage area away from any potential contaminant sources (air, water or soil) or by using plastic sheeting spread on the ground for temporary storage adjacent to the work area. An additional discussion on decontamination of equipment can be found in the section entitled, "Decontamination. "

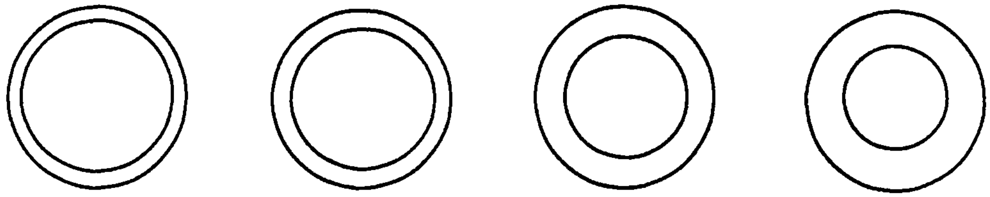
Casing Cost

As Scalf et al. (1981) point out, the dilemma for the field investigator often is the relationship between cost and accuracy. The relative cost of PVC is approximately one tenth the cost of fluoropolymer materials. Cost is always a consideration for any ground-water monitoring project and becomes increasingly important as the number and/or depth of the wells increases. However, if the particular components of interest in a monitoring program are also components of the casing, then the results that are potentially attributable to the casing will be suspect. If the contaminants to be determined are already defined and they do not include chemical constituents that could potentially leach from or sorb onto PVC well casing (as defined by laboratory studies), it may be possible to use PVC as a less expensive alternative to other materials.

Monitoring Well Intakes

Proper design of a hydraulically efficient monitoring well in unconsolidated geologic materials and in certain types of poorly-consolidated geologic materials requires that a well intake be placed opposite the zone to be monitored. The intake should be surrounded by materials that are coarser; have a uniform grain size; and have a higher permeability than natural formation material. This allows ground water to flow freely into the well from the adjacent formation material while minimizing or eliminating the entrance of fine-grained materials (clay, silt, fine sand) into the well. When the well is properly designed and developed, the well can provide ground-water samples that are free of suspended solids. Sediment-free water reduces the potential for interference in sample analyses and eliminates or reduces the need for field sample filtration.

These purposes can be accomplished by designing the well in such a way that either the natural coarse-grained formation materials or artificially introduced coarse-grained materials, in conjunction with appropriately sized intake (well screen) openings, retain the fine materials outside the well while permitting water to enter (United States Environmental Protection Agency, 1975). Thus, there are two types of wells and well intake designs for wells installed in unconsolidated or poorly-consolidated geologic materials: naturally developed wells and wells with an artificially introduced filter pack. In both types of wells, the objective of a filter pack is to increase the effective diameter of the well and to surround the well intake with an envelope of relatively coarse material of greater permeability than the natural formation material.



Schedule 5 (Stainless Steel) — Schedule 10 (Stainless Steel) — Schedule 40 (Stainless Steel, PVC, Fluoropolymer) — Schedule 80 (PVC, Fluoropolymer)

Wall Thickness (Inches)	Sch 5	Sch 10	Sch 40	Sch 80	Outside Diameter (Standard)
Nominal 2	0.065	0.109	0.154	0.218	2.375
Nominal 3	0.083	0.120	0.216	0.300	3.500
Nominal 4	0.083	0.120	0.237	0.337	4.500
Nominal 5	0.109	0.134	0.258	0.375	5.563
Nominal 6	0.109	0.134	0.280	0.432	6.625
Inside Diameter	**Sch 5**	**Sch 10**	**Sch 40**	**Sch 80**	
Nominal 2	2.245	2.157	2.067	1.939	
Nominal 3	3.334	3.260	3.068	2.900	
Nominal 4	4.334	4.260	4.026	3.826	
Nominal 5	5.345	5.295	5.047	4.813	
Nominal 6	6.407	6.357	6.065	5.761	

Figure 53. Effect of casing wall thickness on casing inside and outside diameter.

In the construction of a monitoring well it is imperative that the natural stratigraphic setting be distorted as little as possible. This requires that the development of void space be minimized in unconsolidated formations. As a consequence, boreholes that are over-sized with regard to the casing and well intake diameter generally should be filter-packed. For example, where 2-inch diameter screens are installed in hollow-stem auger boreholes an artificial filter pack is generally recommended. This prevents the collapse of the borehole around the screen with the subsequent creation of void space and the loss of stratification of the formation. Collapse also frequently results in the failure of well seals emplaced on top of the collapsed zone, although well development prior to seal installation may help to minimize this potential problem.

Naturally-Developed Wells

In a naturally-developed well, formation materials are allowed to collapse around the well intake after it has been installed in the borehole. The high-permeability envelope of coarse materials is developed adjacent to the well intake in situ by removing the fine-grained materials from natural formation materials during the well development process.

As described in Driscoll (1986), the envelope of coarse-grained, graded material created around a well intake during the development process can be visualized as a series of cylindrical zones. In the zone adjacent to the well screen, development removes particles smaller than the screen openings leaving only the coarser material in place. Slightly farther away, some medium-sized grains remain mixed with coarse materials. Beyond that zone, the material gradually grades back to the original character of the water-bearing formation. By creating this succession of graded zones around the screen, development stabilizes the formation so that no further movement of fine-grained materials will take place and the well will yield sediment-free water at maximum capacity (Figure 54).

The decision on whether or not a well can be naturally developed is generally based on geologic conditions, specifically the grain-size distribution of natural formation materials in the monitored zone. Wells can generally be naturally developed where formation materials are relatively coarse-grained and permeable. Grain-size distribution is determined by conducting a sieve analysis of a sample or samples taken from the intended screened interval. For this reason, the importance of obtaining accurate formation samples cannot be overemphasized.

After the sample(s) of formation material is sieved, a plot of grain size versus cumulative percentage of sample retained on each sieve is made (Figure 55). Well intake opening sizes are then selected, based on this grain size distribution and specifically on the effective size and uniformity coefficient of the formation materials. The effective size is equivalent to the sieve size that retains 90 percent (or passes 10 percent) of the formation material (Figure 56); the uniformity coefficient is the ratio of the sieve size that will retain 40 percent (or pass 60 percent) of the formation material to the effective size (Figure 57). A naturally-developed well can be considered if the effective grain size of the formation material is greater than 0.01 inch and the uniformity coefficient is appropriate.

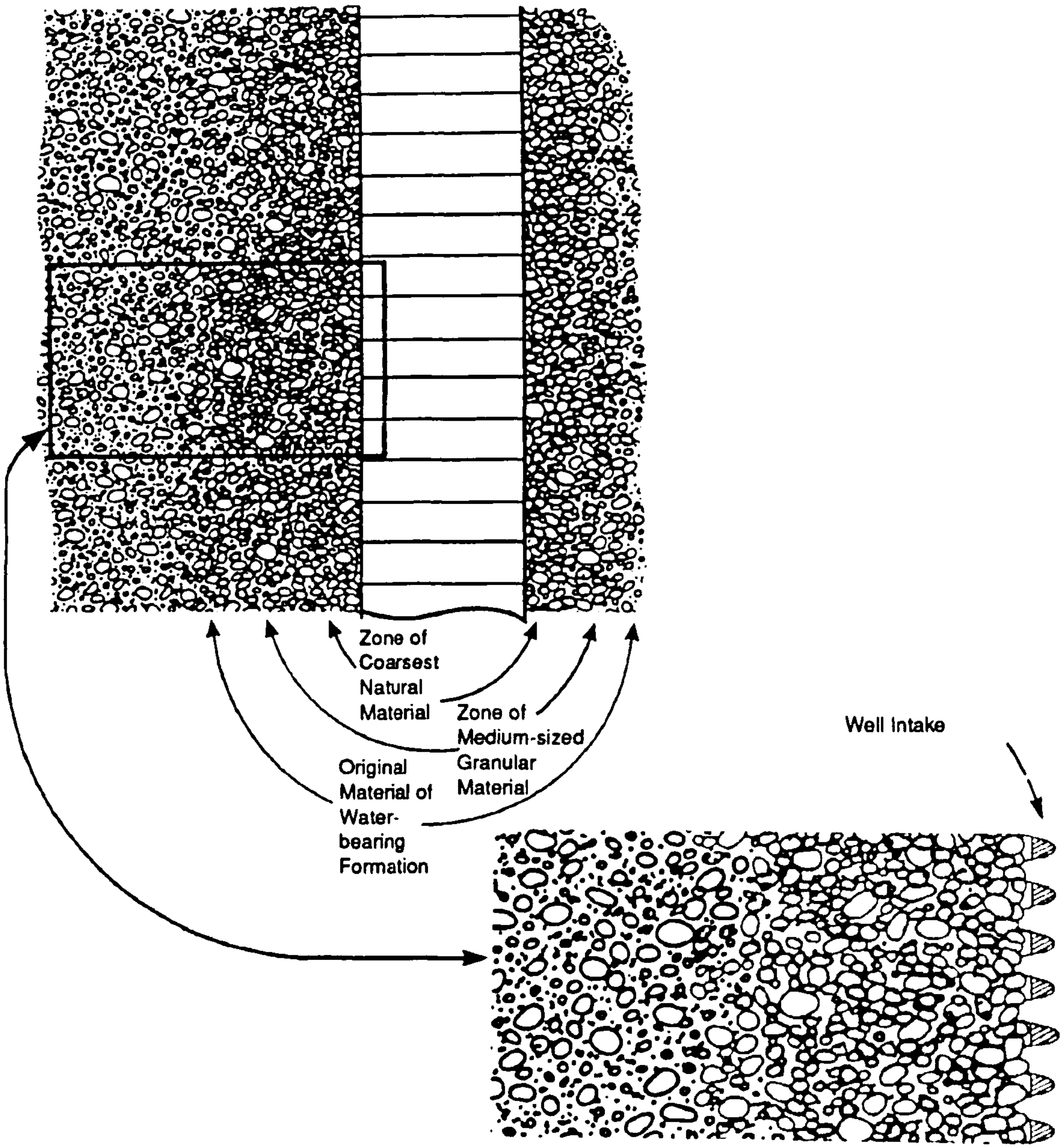


Figure 54. Envelope of coarse-grained material created around a naturally developed well.

In monitoring well applications, naturally-developed wells can be used where the maximum borehole diameter closely approximates the outside diameter of the well intake. By maintaining a minimum space between the well casing and the borehole face, the disturbance of natural stratigraphic conditions is minimized. If these conditions are not observed, the radius of disturbance reduces the probability that ambient flow conditions can be restored.

Artificially Filter-Packed Wells

When the natural formation materials surrounding the well intake are deliberately replaced by coarser, graded material introduced from the surface, the well is artificially filter packed. The term "gravel pack" is also frequently used to describe the artificial material added to the borehole to act as a filter. Because the term "gravel" is classically used to describe large-diameter granular material and because nearly all coarse material emplaced artificially in wells is an engineered blend of coarse to medium sand-sized material, the use of the terms "sand pack" or "filter pack" is preferred in this document. Gravel-sized particles are rarely used as filter pack material because gravel does not generally serve the intended function of a filter pack in a monitoring well.

The artificial introduction of coarse, graded material into the annular space between a centrally-positioned well intake and the borehole serves a variety of purposes. Similar to naturally-developed filter pack, the primary purpose of an artificial filter pack is to work in conjunction with the well intake to filter out fine materials from the formation adjacent to the well. In addition, the artificial filter pack stabilizes the borehole and minimizes settlement of materials above the well intake. The introduction of material coarser than the natural formation materials also results in an increase in the effective

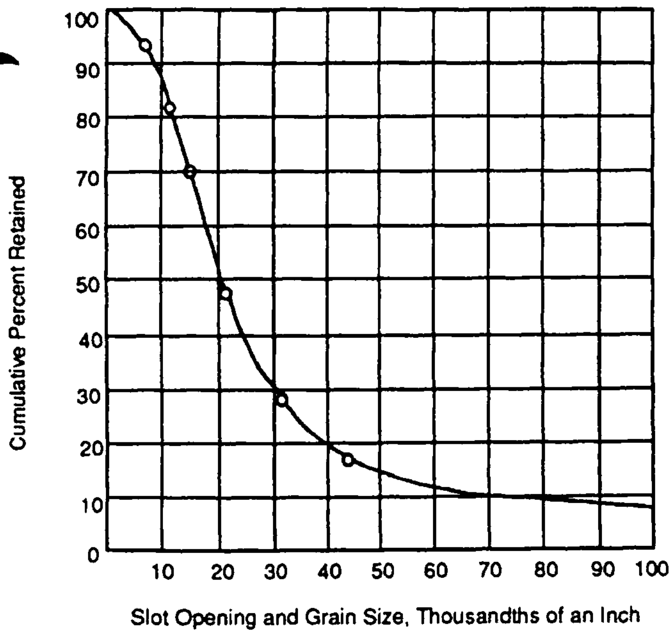


Figure 55. Plot of grain size versus cumulative percentage of sample retained on sieve.

diameter of the well and in an accompanying increase in the amount of water that flows toward and into the well (Figure 58).

There are several geologic situations where the use of an tificial filter pack material is recommended:

1) when the natural formation is uniformly fine-grained (i.e., fine sand through clay-sized particles);
2) when a long screened interval is required and/or the intake spans highly stratified geologic materials of widely varying grain sizes;
3) when the formation in which the intake will be placed is a poorly cemented (friable) sandstone;
4) when the formation is a fractured or solution-channeled rock in which particulate matter is carried through fractures or solution openings;
5) when the formation is shales or coals that will act as a constant supply of turbidity to any ground-water samples; and
6) when the diameter of the borehole is significantly greater than the diameter of the screen.

The use of an artificial filter pack in a fine-grained geologic material allows the intake opening (slot) size to be considerably larger than if the intake were placed in the formation material without the filter pack. This is particularly true where silts and clays predominate in the zone of interest and where fine opening sizes in well intakes to hold out formation materials are either impractical or not commercially available. The larger intake opening size afforded by artificial filter pack emplacement thus allows for the collection of adequate volumes of ·diment-free samples and results in both decreased head loss ..id increased well efficiency.

Filter packs are particularly well-suited for use in extensively stratified formations where thin layers of fine-grained materials alternate with coarser materials. In such a geologic environment, it is often difficult to precisely determine the position and thickness of each individual stratum and to choose the correct position and opening size for a well intake. Completing the well with an artificial filter pack, sized and graded to suit the finest layer of a stratified sequence, resolves the latter problem and increases the possibility that the well will produce water free of suspended sediment.

Quantitative criteria exist with which decisions can be made concerning whether a natural or an artificial filter pack should be used in a well (Campbell and Lehr, 1973; United States Environmental Protection Agency, 1975; Williams, 1981; Driscoll, 1986). Generally the use of an artificial filter pack is recommended where the effective grain size of the natural formation materials is smaller than 0.010 inch and the uniformity coefficient is less than 3.0. California Department of Health Services (1986) takes a different approach and suggests that an artificial filter pack be employed if a sieve analysis of formation materials indicates that a slot size of 0.020 inches or less is required to retain 50 percent of the natural material.

Economic considerations may also affect decisions concerning the appropriateness of an artificial filter pack. Costs associated with filter-packed wells are generally higher than those associated with naturally developed wells, primarily because specially graded and washed sand must be purchased and transported to the site. Additionally, larger boreholes are necessary for artificially filter-packed wells (e.g., suggested minimum 6-inch diameter borehole for a 2-inch inside diameter well or 8-inch borehole for a 4-inch well).

An alternate design for the artificial filter pack is provided by the "pre-packed" well intake. There are two basic designs that are commercially available: 1) single-wall prepack and 2) double-wall prepack. The single-wall prepack is fabricated by bonding well-sorted siliceous grains onto a perforated pipe base. Epoxy-based bonds have been the most commonly used, although other types of bonding materials have also been employed. The double-wall prepack consists of an unbonded granular layer of well-sorted silica grains between two perforated casings. The advantage of the double-wall system is that it is extremely strong and should not have chemical questions from bonding agent used in single wall.

The advantages of prepack well intakes are: 1) ease of installation in either a stable borehole or within boreholes protected by auger flights or casing (by the pullback method) and 2) the ability if properly sized to provide filtration of even the finest formations, thereby effectively minimizing turbidity in otherwise "difficult if not impossible to develop formations." The disadvantages of this type of well intake are: 1) the bonding material for the single-wall design may create chemical interference; 2) wells with prepack screens are difficult to redevelop if plugging occurs; and 3) commercial availability of this design has been extremely variable through time. The single-wall epoxy-based well intake is presently available only on an import basis; the double-wall well intake is currently available from at least one domestic manufacturer.

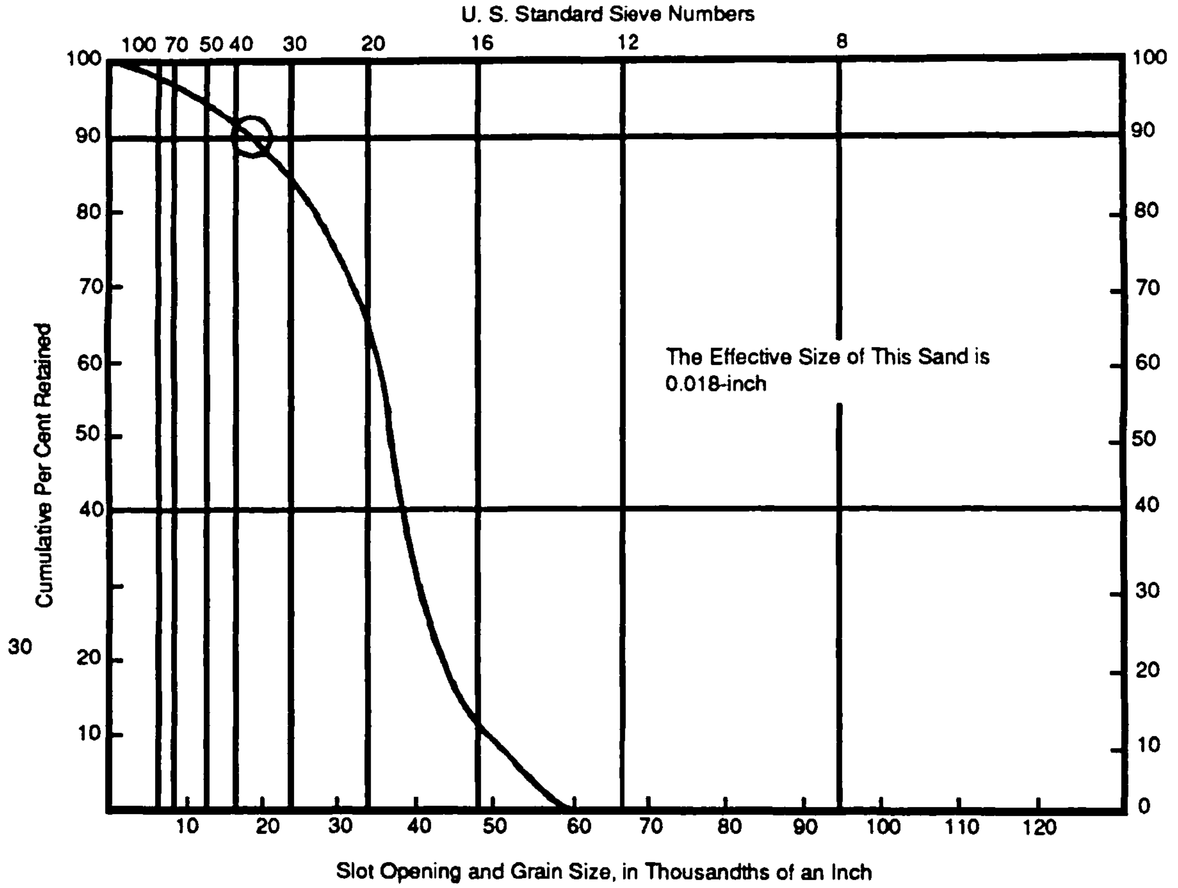


Figure 56. Determining effective size of formation materials.

Filter Pack Design —

Artificial filter pack design factors for monitoring wells include: 1) filter pack grain size; 2) intake opening (slot) size and length; 3) filter pack length, 4) filter pack thickness and 5) filter pack material type. When an artificial filter pack is dictated by sieve analysis or by geologic conditions, the filter pack grain sizes and well intake opening sizes are generally designed as a single unit.

The selection of filter pack grain size and well intake opening size is a function of the formation. The filter pack is designed first because it is the interface with the aquifer. The first step in designing the filter pack is to obtain samples of the formation intended to be monitored and perform sieve analyses on the samples. The filter pack material size is then selected on the basis of the finest formation materials present.

Although design techniques vary, all use the filter pack ratio to establish size differential between the formation materials and filter pack materials. Generally this ratio refers to either the average (50 percent retained) grain size of the formation material or the 70 percent retained size of the formation material. For example, Walker (1974) and Barcelona et al. (1985a) recommend using a uniform filter pack grain size that is 3 to 5 times the 50 percent retained size of the formation materials. Driscoll (1986) recommends a more conservative approach by suggesting that for fine-grained formations, the 50 percent retained size of the finest formation sample be multiplied by a factor of 2 to exclude the entrance of fine silts, sands and clays into the monitoring well. The United States Environmental Protection Agency (1975) recommends that filter pack grain size be selected by multiplying the 70 percent retained grain size of the formation materials by a factor between 4 and 6. A factor of 4 is used if the formation is fine and uniform; a factor of 6 is used if the formation is coarser and non-uniform. In both cases, the uniformity coefficient of the filter pack materials should not exceed 2.5 and the gradation of the filter material should form a smooth and gradual size distribution

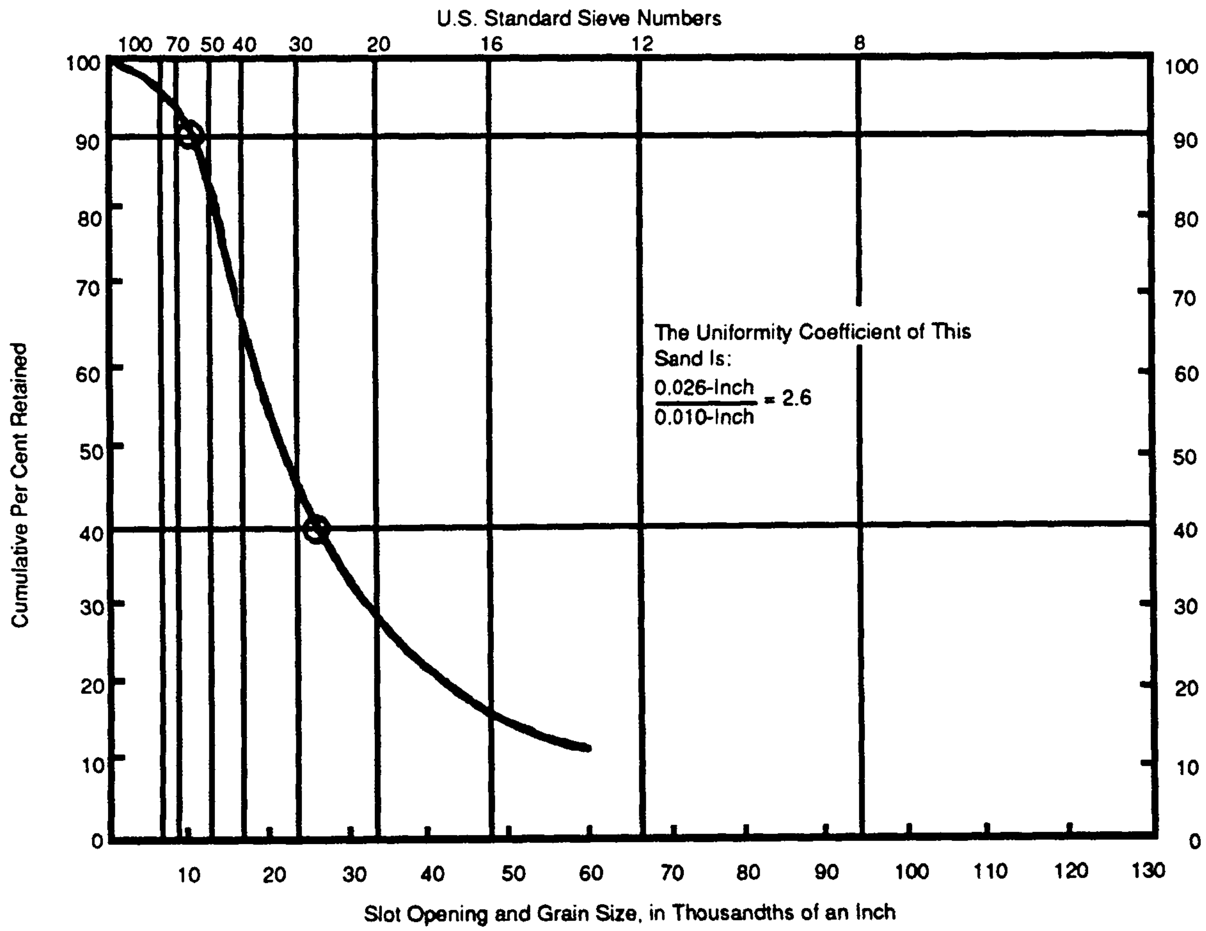


Figure 57. Determining uniformity coefficient of formation materials.

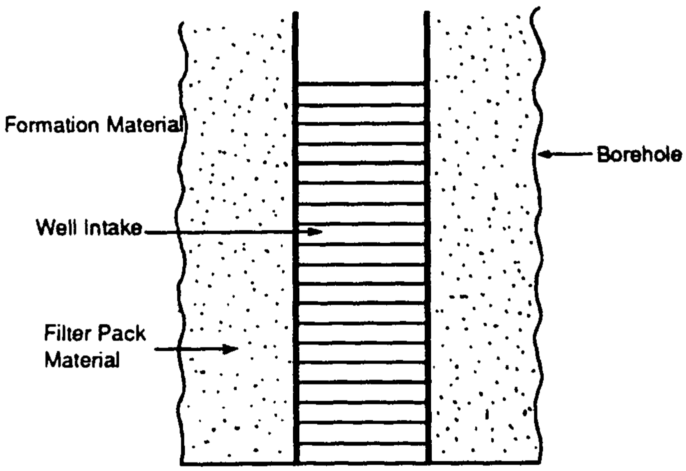


Figure 58. Envelope of coarse-grained material emplaced around an artificially filter-packed well.

when plotted (Figure 59). The actual filter pack used should fall within the area defined by these two curves. According to Williams (1981), in uniform formation materials, either approach to filter pack material sizing will provide similar results; however in coarse, poorly sorted formation materials, the average grain size method may be misleading and should be used with discretion.

Two types of artificial filter packs are possible for use in production wells: 1) the uniform, well-sorted grain size filter pack and 2) the graded grain-size filter pack. Uniform filter packs are generally preferred to graded packs for monitoring wells. Graded packs are more susceptible to the invasion of formation materials at the formation-filter pack interface. This invasion results in a partial filling of voids between grains and a concomitant reduction in permeability. Graded packs are also difficult to install in the limited annular space available without segregation of the filter pack material. With a uniform filter pack, the fine formation materials can travel between the grains of the pack and be pulled into the well during development. When this occurs, the formation permeability is increased and the high permeability of the filter pack is also retained.

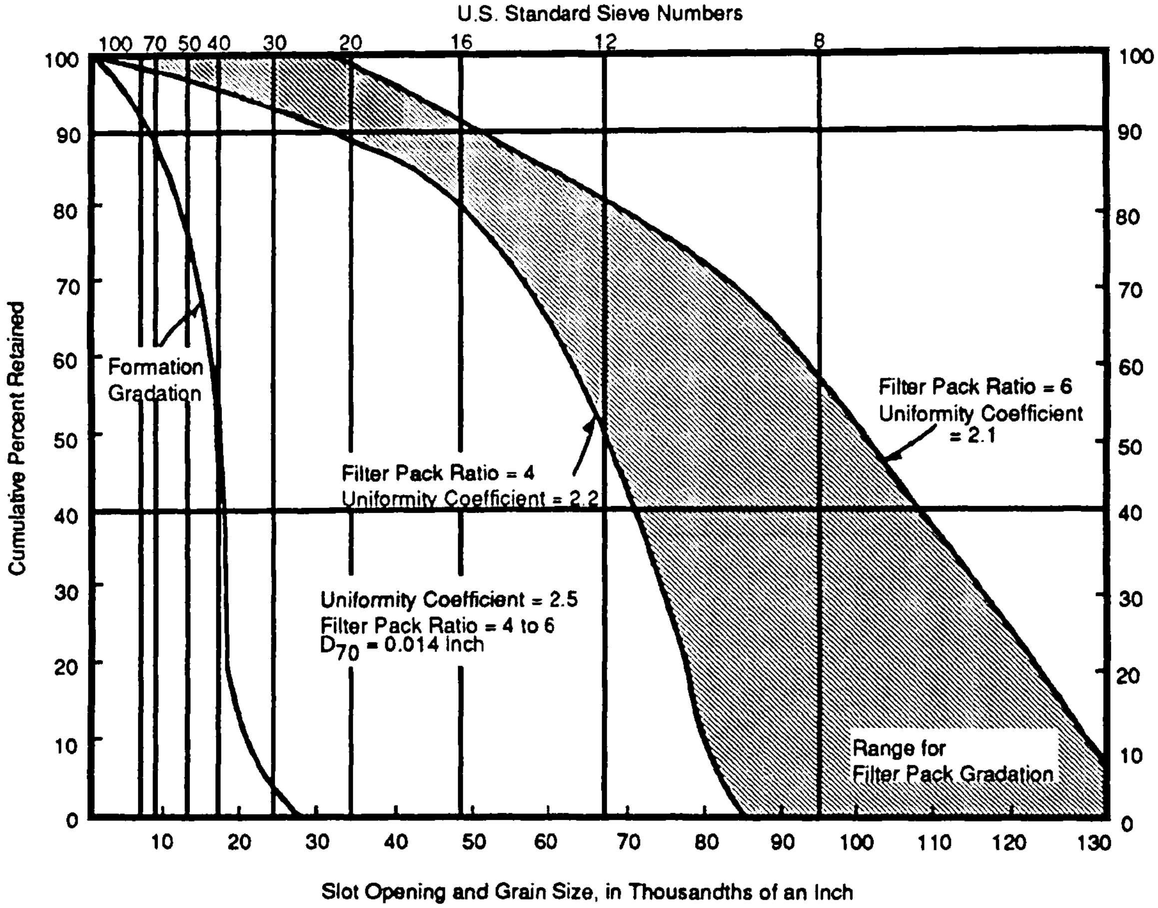


Figure 59. Artificial filter pack design criteria.

The size of well intake openings can only be selected after the filter pack grain size is specified. The opening (slot) size is generally chosen on the basis of its ability to hold back between 85 percent and 100 percent of' the filter pack materials (United States Environmental Protection Agency, 1975) (Figure 60).

Filter Pack Dimensions —

The filter pack should generally extend from the bottom of the well intake to approximately 2 to 5 feet above the top of the well intake provided the interval above the well intake does not result in cross-connection with an overlying zone. If cross-connection is a potential problem, then the design may need to be adjusted. The filter pack placed above the intake allows for settlement of the filter pack material that occurs during well development and allows a sufficient "buffer" between the well intake and the annular seal above.

The filter pack must be at least thick enough to surround the well intake completely but thin enough to minimize resistance caused by the filter pack to the flow of water into the well during development. To accommodate the filter pack, the well intake should be centered in the borehole and the annulus should be large enough and approximately symmetrical to preclude bridging and irregular placement of filter pack material. A thicker filter pack neither increases the yield of the well nor reduces the amount of fine material in the water flowing to the well (Ahrens, 1957). Most references in the literature (Walker, 1974; United States Environmental Protection Agency, 1975; Williams, 1981; Driscoll, 1986) suggest that a filter pack thickness of between 3 and 8 inches is optimum for production wells. A thin filter pack is preferable from the well-development perspective, because it is difficult to develop a well with a thick filter pack. Conversely, it is difficult to reliably construct a well with a filter pack that is less than 2 inches thick. Monitoring well filter pack thicknesses are commonly suggested to be at least 2 to 4 inches. Methods to calculate the volume of filter pack necessary are contained in Appendix A in the section entitled "Installation of the Filter Pack."

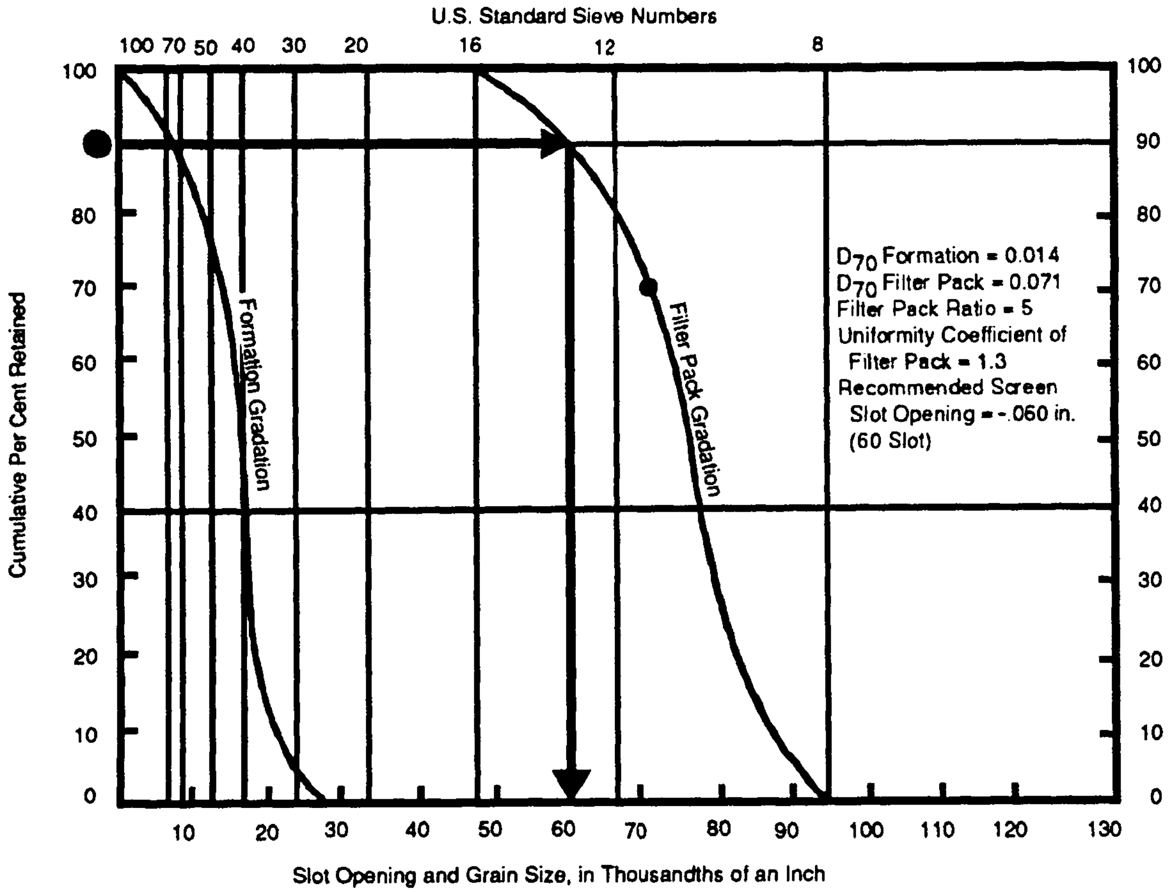


Figure 60. Selecting well intake slot size based on filter pack grain size.

Filter Pack Materials —

The materials comprising the filter pack in a monitoring well should be chemically inert to alleviate the potential for alteration of ground-water sample chemical quality. Barcelona et al. (1985b) suggest that the filter pack materials should be composed primarily of clean quartz sand or glass beads. The individual grains of the filter pack materials should be well-rounded and consist of less than 5 percent non-siliceous material (Driscoll, 1986). For natural materials, well rounded quartz is preferred because quartz is nonreactive in nearly all ground-water conditions and is generally available. A filter pack comprised of other types of crushed stone should not be used because of potential chemical alteration of ground water and problems from non-rounded material. If crushed limestone is used, the alterations may be particularly significant and pH modifications can be expected. Shale and carbonaceous material should also be avoided.

Well Intake Design

Monitoring well intake design factors include: 1) intake opening (slot) size, 2) intake length, 3) intake type and 4) corrosion and chemical degradation resistance. Proper sizing of monitoring well intake openings is one of the most important aspects of monitoring well design. There has been in the past a tendency among some monitoring well designers to install a "standard" or common slot size (e.g., 0.010 inch slots) in every well, with no site-specific design considerations. As Williams (1981) points out, this can lead to difficulties with well development, poor well performance or, in some severe cases, well failure.

Well Intake Opening Sizes —

For artificially filter packed wells, the well intake opening sizes are selected as previously discussed and illustrated in Figure 60. For naturally packed wells, well intake opening sizes are generally selected based on the following criteria that were developed primarily for production wells:

1) where the uniformity coefficient of the formation material is greater than 6 and the material above the intended screened interval is non-caving, the slot size should be that which retains no less than 30 percent of formation material;
2) where the uniformity coefficient of the formation material is greater than 6 and the material above the intended screened interval is readily-caving, the slot size should be that which retains no less than 50 percent of formation material;
3) where the uniformity coefficient of the formation

material is less than 3 and the material above the intended screened interval is non-caving, the slot size should be that which retains no less than 40 percent of formation material;

4) where the uniformity coefficient of the formation material is less than 3 and the material above the intended screened interval is readily-caving, the slot size should be that which retains no less than 60 percent of formation material; and

5) where an interval to be monitored has layered formation material of differing sizes and gradations, and where the 50 percent grain size of the coarsest layer is less than 4 times the 50 percent size of the finest layer, the slot size should be selected on the basis of the finest layer. Otherwise, separate screened sections should be sized for each zone.

Because these criteria were developed for production wells, those factors that enhance yield are overemphasized. The objective of a monitoring well is frequently to obtain a water quality sample that is representative of the in-situ ground-water quality. Hence it is imperative to minimize disturbance or distortion of flow lines from the aquifer into the well. To achieve this objective, construction activities that result in caving, void space or modification of the stratigraphy in the vicinity of the wellbore must be avoided or minimized. Procedures for attaining this objective have been discussed in this chapter in the section entitled "Naturally-Developed Wells" and in Section 4 in the part entitled "Ability of Drilling Technology to Preserve Natural Conditions."

The slot size determined from a sieve analysis is seldom that of commercially available screen slot sizes (Table 33), so the nearest smaller standard slot size is generally used. In most monitoring wells, because optimum yield from the well is not as critical to achieve as it is in production wells and because extensive development is more difficult to accomplish in small-diameter monitoring wells, screens are usually designed to have smaller openings than indicated by the above-stated design criteria so that less formation material will be pulled into the well during the development.

Well Intake Length Selection —

The selection of the length of a monitoring well intake depends on the purpose of the well. Most monitoring wells function as both ground-water sampling points and piezometers for a discrete interval. To accomplish these objectives, well intakes are typically 2 to 10 feet in length, and only rarely equal or exceed 20 feet in length. Shorter intakes provide more specific information about vertically-distributed water quality, hydraulic head and flow in the monitored formation. However, if the objective of the well is to monitor for the gross presence of contaminants in an aquifer, a much longer screen can be selected to monitor a greater thickness of the aquifer. This type of well can provide an integrated water sample and an integrated hydraulic head measurement as well as access for vertical profiling.

There are also situations where the "flow-through"-type well is preferable. In a flow-through installation, a small-diameter screen of 2 inches diameter or less, is installed to fully penetrate an aquifer, or to at least penetrate a significant portion of the aquifer. The diameter of the screen is small so that minimal distortion of the flow field in the aquifer is created. Borehole geochemical profiling is used to evaluate vertical variations in contaminant flow; spot sampling can be used to provide zone characterization with minimal vertical mixing. By slowly lowering a geochemical probe into the borehole, measurements of parameters such as pH, Eh, conductivity, dissolved oxygen and temperature can be taken at close intervals (e.g. 1-foot, 2-foot or 5-foot intervals). These measurements can be recorded successively from the top of the saturated zone to the bottom of the screened interval with very slight disturbance to the zone being measured. Measurements are taken as the probe is lowered because vertical mixing in the borehole can be expected to occur as the probe is withdrawn.

Once sufficient time has passed after sampling for indigenous conditions to be reestablished, a grab sampler can be lowered to the uppermost zone of interest and a water quality sample obtained. By slowly and carefully sampling successively deeper zones, a series of relatively undisturbed water quality samples can be collected for laboratory analysis. The laboratory results can subsequently be compared with the data obtained from the geochemical probe. The method of geochemical evaluation is particularly valuable for evaluating three-dimensional flow in a stratified but relatively homogeneous aquifer such as fluvial sands and gravels.

Well Intake Type —

The hydraulic efficiency of a well intake depends primarily on the amount of open area available per unit length of intake. While hydraulic efficiency is of secondary concern in monitoring wells, increased open area in monitoring well intakes also permits easy flow of water from the formation into the well and allows for effective well development. The amount of open area in a well intake is controlled by the type of well intake and opening size.

Many different types of intakes are available for use in production wells; several of these are also suitable for use in monitoring wells. Commercially-manufactured well intakes are recommended for use in monitoring wells because stricter quality control measures are followed by commercial manufacturers. Hand-slotted or drilled casings should not be used as monitoring well intakes because there is poor control over the intake opening size, lack of open area and potential leaching and/or chemical problems at the fresh surfaces exposed by hand sawing or drilling. Similarly, casing that has been perforated either by the application of a casing knife or a perforating gun after the casing is installed in the borehole is not recommended because intake openings cannot be closely spaced, the percentage of open area is low, the opening sizes are highly variable and opening sizes small enough to control fine materials are difficult or impossible to produce. Additionally, perforation tends to hasten corrosion attack on metal casing because the jagged edges and rough surfaces of the perforations are susceptible to selective corrosion.

Many commercially-manufactured well intakes have been used in monitoring wells including: 1) the louvered (shutter-type) intake, 2) the bridge-slot intake, 3) the machine-slotted well casing and 4) *the continuous-slot* wire-wound intake (Figure 61). The latter two types of intakes are used most

Table 33. Correlation Chart of Screen Openings and Sieve Sizes (Driscoll, 1986)

Geologic Material Grain-size Range	Johnson Slot No.	Gauze No.	Tyler Sieve No.	Tyler Size of Openings Inches	Tyler Size of Openings mm	U.S Standard Sieve No.	U.S Standard Size of Openings Inches
clay & silt	-	-	400	0.0015	0.038	400	0.0015
	-	-	325	0.0017	0.043	325	0.0017
	-	-	270	0.0021	0.053	270	0.0021
	-	-	250	0.0024	0.061	230	0.0024
		-	200	0.0029	0.074	200	0.0029
fine sand	-	-	170	0.0035	0.088	170	0.0035
	-	-	150	0.0041	0.104	140	0.0041
	-	-	115	0.0049	0.124	120	0.0049
	6	90	100	0.0058	0.147	100	0.0059
	7	80	80	0.0069	0.175	80	0.0070
	8	70	65	0.0082	0.208	70	0.0083
	10	60	60	0.0097	0.246	60	0.0098
medium sand	12	50	48	0.0116	0.295	50	0.0117
	14	-	42	0.0138	0.351	45	0.0138
	16		35	0.0164	0.417	40	0.0165(1/64)
	18	40	-	0.0180	0.457	-	0.0180
	20		32	0.0195	0.495	35	0.0197
	23		28	0.0232	0.589	30	0.0232
coarse sand	25	30	-	0.0250	0.635	-	0.0250
	28		24	0.0276	0.701	25	0.0280
	31		-	0.0310	0.788	-	0.0310(1/32)
	33		20	0.0328	0.833	20	0.0331
	35	20	-	0.035	0.889	-	0.0350
	39		16	0.039	0.991	18	0.0394
very coarse sand	47		14	0.046	1.168	16	0.0469
	56		12	0.055	1.397	14	0.0555
	62		-	0.062	1.590	-	0.062(1/16)
	66		10	0.065	1.651	12	0.0661
	79		9	0.078	1.981	10	0.0787
very fine gravel	93		8	0.093	2.362	8	0.0931
	94		-	0.094	2.390	-	0.094(3/32)
	111		7	0.110	2.794	7	0.111
	125		-	0.125	3.180	-	0.125(1/8)
	132		6	0.131	3.327	6	0.132
fine gravel	157		5	0.156	3.962	5	0.157
	187		4	0.185	4.699	4	0.187(3/16)
	223		31/2	0.221	5.613	31/2	0.223
	250		-	0.250	6.350	1/4	0.250(1/4)
	263		3	0.263	6.680	-	0.263
	312		21/2	0.312	7.925	5/16	0.312(5/16)
	375		0.371	0.371	9.423	3/8	0.375(3/8)
	438		0.441	0.441	11.20	7/16	0.438(7/16)
	500		0.525	0.525	13.33	1/2	0.500(1/2)

extensively because they are the only types available with 2-inch inside diameters.

The louvered (shutter-type) screen has openings that are manufactured in solid-wall metal tubing by stamping outward with a punch against dies that limit the size of the openings (Helweg et al., 1984). The number and sizes of openings that can be made depends on the series of die sets used by individual manufacturers. Because a complete range of die sets is impractical, the opening sizes of commercially-available screens are somewhat limited. Additionally, because of the large blank spaces that must be left between adjacent openings, the percentage of open area on louvered intakes is limited. Louvered well intakes are primarily used in artificially-packed wells because the shape of the louvered openings is such that the shutter-type intakes are more difficult to develop in naturally-packed wells. This type of intake, however, provides greater collapse strength than most other intakes.

Bridge-slot screen is manufactured on a press from flat sheets or plates of metallic material that are rolled into cylinders and seam-welded after being perforated. The slot opening is usually vertical with two parallel openings longitudinally aligned to the well axis. Five-foot sections of bridge-slot screen that can be welded into longer screen sections if desired are commonly available. The advantages of bridge-slot screen include: a reasonably high intake opening area, minimal frictional head losses and low cost. One important disadvantage is low collapse strength that is caused by the presence of a large number of vertically-oriented slots. The use of this type of intake is limited in monitoring well application because it is only produced in diameters 6 inches and larger.

Slotted well intakes are fabricated from standard well casing by cutting horizontal (circumferential) or vertical (axial) slots of predetermined widths at regular intervals with machining tools. Slotted well casing can be manufactured from any casing material although these intakes are most commonly made from thermoplastic, fluoropolymer and fiberglass-reinforced epoxy materials. This type of intake is available in diameters ranging from 3/4 inch to 16 inches (National Water Well Association and Plastic Pipe Institute, 1981). Table 34 lists the most common slot widths of slotted well casing.

Table 34. Typical Slotted Casing Slot Widths (National Water Well Association and Plastic Pipe Institute, 1981)

0.006	0.016	0.040
0.007	0.018	0.050
0.008	0.020	0.060
0.010	0.025	0.070
0.012	0.030	0.080
0.014	0.035	0.100

The continuous slot wire-wound intake is manufactured by winding cold-drawn wire, approximately triangular in cross section, spirally around a circular array of longitudinally arranged rods (Figure 62). At each point where the wire crosses the rods, the two members are securely joined by welding, creating a one-piece rigid unit (Driscoll, 1986) Continuous-slot intakes can be fabricated of: 1) any metal that can be resistance-welded, including bronze, silicon red brass, stainless steel (104 and 316), galvanized and low-carbon steel and 2) any thermoplastic that can be sonic-welded, including polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS).

The slot openings of continuous-slot intakes are produced by spacing the successive turns of the wire as desired. This configuration provides significantly greater open area per given length and diameter than is available with any other intake type. For example, for 2-inch inside diameter well intake, the open area ranges from approximately 4 percent for the smallest slot size (0.006 inch) to more than 26 percent for the largest slot size (0.050 inch) (Table 35). Continuous-slot intakes also provide a wider range of available slot sizes than any other type of intake and have slot sizes that are accurate to within ±0.003 inch (Ahrens, 1970). The slot openings are designated by numbers that correspond to the width of the opening in thousandths of an inch. A number 10 slot, for example, refers to an opening of 0.010 inch.

The continuous-slot intake also is more effective in preventing formation materials from becoming clogged in the openings. The triangular-shaped wire is wound so that the slot openings between adjacent wires are V-shaped, with sharp outer edges; the slots are narrowest at the outer face and widen inwardly. This makes the intakes non-clogging because particles slightly smaller than the openings can pass freely into the well without wedging in the opening.

Well Intake Material Properties —

The intake is the part of the monitoring well that is most susceptible to corrosion and/or chemical degradation and provides the highest potential for sorption or leaching phenomena to occur. Intakes have a larger surface area of exposed material than casing, are placed in a position designed to be in contact with potential contaminants (the saturated zone) and are placed in an environment where reactive materials are constantly being renewed by flowing water. To avoid corrosion, chemical degradation, sorption and leaching problems, the materials from which intakes are made are selected using the same guidelines as for casing materials.

Annular Seals

Purpose of the Annular Seal

Any annular space that is produced as the result of the installation of well casing in a borehole provides a channel for vertical movement of water and/or contaminants unless the space is sealed. In any casing/borehole system, there are several potential pathways for water and contaminants (Figure 63). One pathway is through the sealing material. If the material is not properly formulated and installed or if it cracks or deterio-

Table 35. Intake Areas (Square Inches per Lineal Foot of Screen) for Continuous Wire-Wound Well Intake (After Johnson Screens, Inc., 1988)

Screen Size (in.)	6 Slot (0.006")	8 Slot (0.008")	10 Slot (0.010")	12 Slot (0.012")	15 Slot (0.015")	20 Slot (0.020")	25 Slot (0.025")	30 Slot (0.030")	35 Slot (0.035")	40 Slot (0.040")	50 Slot (0.050")
1 1/4 PS*	3.0	3.4	4.8	6.0	7.0	8.9	10.8	12.5	14.1	15.6	18.4
2 PS	3.0	3.4	4.8	6.0	7.0	8.9	10.8	12.5	14.1	15.6	18.4
1 1/2 PS	3.4	4.5	5.5	6.5	8.1	10.2	12.3	14.2	16.2	17.9	20.1
2 PS	4.3	5.5	6.8	8.1	10.0	12.8	15.4	17.9	20.3	22.4	26.3
3 PS	5.4	7.1	8.8	10.4	12.8	16.5	20.0	23.2	26.5	29.3	34.7
4 PS	7.0	9.0	11.3	13.5	16.5	21.2	25.8	30.0	33.9	37.7	44.5
4 Spec**	7.4	9.7	11.9	14.2	17.2	22.2	27.1	31.3	35.5	39.7	46.8
4 1/2 PS	7.1	9.4	11.7	13.8	17.0	21.9	26.8	31.0	35.2	39.4	46.5
5 PS	8.1	10.6	13.1	15.5	19.1	24.7	30.0	34.9	39.7	44.2	52.4
6 PS	8.1	10.6	13.2	15.6	19.2	25.0	30.5	35.8	40.7	45.4	54.3
8 PS	13.4	17.6	21.7	25.7	31.5	40.6	49.3	57.4	65.0	72.3	85.6

The maximum transmitting capacity of screens can be derived from these figures. To determine GPM per ft of screen, multiply the intake area in square inches by 0.31. It must be remembered that this is the maximum capacity of the screen under ideal conditions with an entrance velocity of 0.1 foot per second.

* PS means pipe size.

** Spec means special.

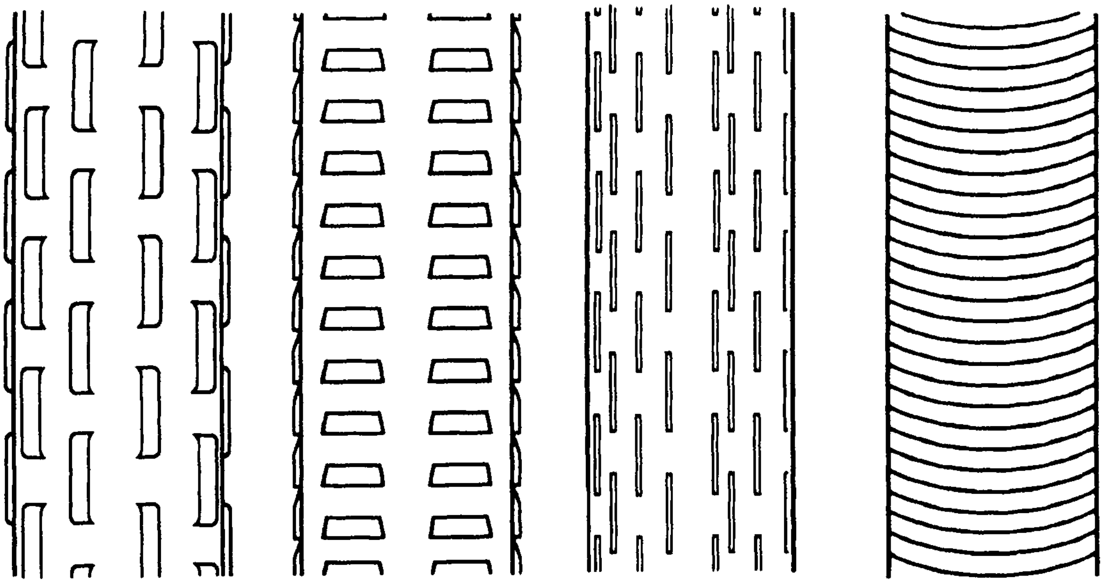


Figure 61. Types of well intakes.

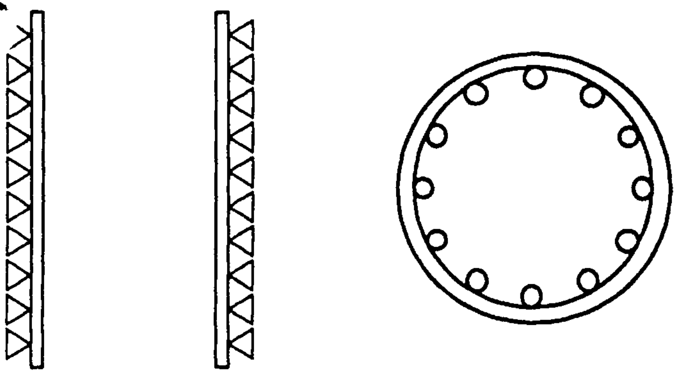


Figure 62. Cross-sections of continuous-wrap wire-wound screen

rates after emplacement, the permeability in the vertical direction can be significant. These pathways can occur because of any of several reasons, including: 1) temperature changes of the casing and sealing material (principally neat cement) during the curing or setting of the sealing material, 2) swelling and shrinkage of the sealing material while curing or setting or 3) poor bonding between the sealing material and the casing (Kurt and Johnson, 1982). Another pathway may result if sealing materials bridge in the annular space. All of these pathways can be anticipated and usually avoided with proper annular seal formulation and placement methods.

The annular seal in a monitoring well is placed above the filter pack in the annulus between the borehole and the well casing. The seal serves several purposes: 1) to provide protection against infiltration of surface water and potential contaminants from the ground surface down the casing/borehole annulus, 2) to seal off discrete sampling zones, both hydraulically and chemically and 3) to prohibit vertical migration of water. Such vertical movement can cause what is referred to as "cross contamination." Cross contamination can influence the representativeness of ground-water samples and can cause an anomalous hydraulic response of the monitored zone, resulting in distorted data. The annular seal increases the life of the casing by protecting it against exterior corrosion or chemical degradation. A satisfactory annular seal results in complete filling of the annular space and envelopes the entire length of the well casing to ensure that no vertical migration can occur within the borehole. Methods to calculate the volume of sealant necessary to fill the annular space are contained in Appendix A in the section entitled "Installation of the Filter Pack." Volume calculations are the same as those performed to calculate filter pack volume.

Materials Used for Annular Seals

According to Moehrl (1964), the material used for an annular seal must:

1) be capable of emplacement from the surface;
2) hydrate or develop sufficient set strength within a reasonably short time;
3) provide a positive seal between the casing and the adjacent formations;
4) be chemically inert to formations or fluids with which it may come in contact;

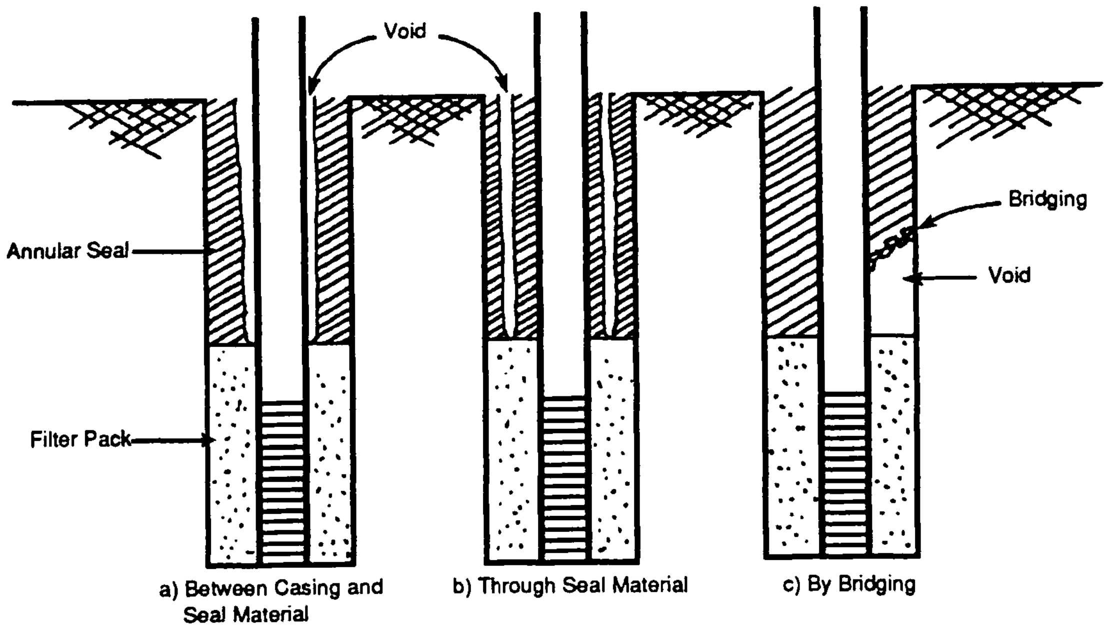


Figure 63. Potential pathways for fluid movement in the casing-borehole annulus.

5) be permanent, stable and resist chemical or physical deterioration; and
6) be sufficiently impermeable to fluids to ensure that the vertical permeability of the casing/ borehole system be lower than that of surrounding formations.

The annular seal may be comprised of several different types of permanent, stable, low-permeability materials including pelletized, granular or powdered bentonite, neat cement grout and combinations of both. The most effective seals are obtained by using expanding materials that will not shrink away from either the casing or the borehole wall after curing or setting. Bentonite, expanding neat cement or mixtures of neat cement and bentonite are among the most effective materials for this purpose (Barcelona et al., 1983; 1985a). If the casing/ borehole annulus is backfilled with any other material (e.g., recompacted, uncontaminated drill cuttings; sand or borrow material), a low permeability seal cannot be ensured and the borehole may then act as a conduit for vertical migration. This is particularly a problem when drill cuttings are used as a seal because recompacted drill cuttings usually have a higher permeability than the natural formation materials from which they are derived.

Bentonite —

Bentonite is a hydrous aluminum silicate comprised principally of the clay mineral montmorillonite. Bentonite possesses the ability to expand significantly when hydrated; the expansion is caused by the incorporation of water molecules into the clay lattice. Hydrated bentonite in water typically expands 10 to 15 times the volume of dry bentonite. Bentonite forms an extremely dense clay mass with an in-place permeability typically in the range of $1x10^{-7}$ to $1x10^{-9}$ cm/sec when hydrated. Bentonite expands sufficiently to provide a very tight seal between the casing and the adjacent formation material, thus making it a desirable sealant for the casing/borehole annulus in monitoring wells.

Bentonite used for the purpose of sealing the annulus of monitoring wells is generally one of two types: 1) sodium bentonite or 2) calcium bentonite. Sodium bentonite is the most widely used because of its greater expandability and availability, Calcium bentonite may be preferable in high-calcium environments because shrinkage resulting from long-term calcium-for-sodium ion exchange is minimized. Bentonite is available in several forms including pellets, granules and powder. Pellets are uniformly shaped and sized by compression of sodium montmorillonite powder. Granules are irregularly shaped and sized particles of sodium montmorillonite. Both pellets and granules expand at a relatively fast rate when exposed to fresh water. The powdered form of bentonite is the form produced by the processing plant after mining. While both pelletized and granular bentonite may be emplaced in dry form, powdered bentonite is generally made into a slurry to allow emplacement.

Bentonite slurry is generally prepared by mixing dry bentonite powder into fresh water in a ratio of approximately 15 pounds of bentonite to 7 gallons of water to yield 1 cubic foot of bentonite slurry. The bentonite and water are mixed by moderate agitation, either manually in a large tank or with a paddle mixer. The use of high-shear mixing equipment increases the viscosity development of the slurry and can reduce the ultimate working time by as much as 20 percent. Thick bentonite slurries may swell quickly into non-pumpable gel masses that cannot be emplaced. Pre-mix and/or polymer (organic and inorganic) additives delay the wetting of the bentonite and prevent premature hydration. Where additives are used, the additives should be evaluated for potential effects on extant ground-water quality. Once the slurry is mixed, it should remain workable for between one-half and two hours. During this time, a positive displacement mud or grout pump (typically a centrifugal, diaphragm, piston or moyno-type pump) is used to emplace the seal at the desired depth.

Bentonite has a high cation exchange capacity. This high cation exchange capacity allows the bentonite to exchange cations that are part of the chemical structure of the bentonite (principally Na, Al, Fe and Mn) with cations that exist in the aqueous solution (e.g., ground water) that hydrates the bentonite. The bentonite may take up or release cations from or into aqueous solution depending on: 1) the chemistry of both the bentonite and the solution and 2) the pH and redox potential of the aqueous solution. In addition to having a high cation exchange capacity, bentonite generally sets up with a moderately high pH between 8.5 and 10.5. Thus, bentonite may have an impact on the quality of ground water with which it comes in contact. In particular, pH and metallic ion content may be affected. If a bentonite seal is placed too close to the top of the well intake, water-quality samples that are not representative of the aquifer may be collected. The suggested practice is to place at least 1 foot of very fine-grained sand on top of the filter pack and to place the bentonite sealing material 2 to 3 feet above the top of the well intake, where possible.

The effective use of bentonite pellets as a sealing material depends on efficient hydration following emplacement. Hydration requires the presence of water of both sufficient quantity and quality within the geologic materials penetrated by the borehole. Generally, efficient hydration will occur only in the saturated zone. Bentonitic materials by themselves are generally not appropriate for use in the vadose zone because sufficient moisture is not available to effect hydration of the bentonite. Certain water-quality conditions inhibit the swelling of bentonite. For example, bentonite mixed with water that has either a total dissolved solids content greater than 500 parts per million or a high chloride content may not swell to occupy the anticipated volume and therefore may not provide an effective seal. The degree of inhibition depends on the level of chlorides or total dissolved solids in the water. Recent studies conducted to determine the effects of some organic solvents and other chemicals (i.e., xylene, acetone, acetic acid, aniline, ethylene glycol, methanol and heptane) on hydrated clays including bentonite have demonstrated that bentonite and other clays may lose their effectiveness as low-permeability barrier materials in the presence of concentrated solutions of selected chemical substances (Anderson et al., 1982; Brown et al., 1983). These studies have shown that the hydraulic conductivity of clays subjected to high concentrations of organic acids, basic and neutral polar organic compounds and neutral non-polar organic compounds may increase by several orders of magnitude due to dessication and dehydration of the clay material. This dessication and dehydration can provide conduits for vertical migration within boreholes in which bentonite is used as sealing material. Villaume (1985) points to possible attack on and loss of integrity of bentonite seals due to dehydration and shrinkage of the clay by hydrocarbons in the free product phase. Thus, where these chemical conditions exist in the subsurface, bentonite may not perform as an effective seal and another material may be necessary.

In summary, factors that should be considered in evaluating the use of bentonite as a sealant include:

1) position of the static water level in a given borehole (including seasonal and other water-level fluctuations);
2) ambient water quality (particularly with respect to total dissolved solids conti'nt and chloride content); and
3) types and potential concentrations of contaminants expected to be encountered in the subsurface.

Cement —

Neat cement is a mixture of Portland cement (ASTM C-150) and water in the proportion of 5 to 6 gallons of clean water per bag (94 pounds or 1 cubic foot) of cement. Five general types of Portland cement are produced: Type I, for general use; Type II, for moderate sulfate resistance or moderate heat of hydration; Type III, for high early strength; Type IV, for low heat of hydration; and Type V, for high sulfate resistance (Moehrl, 1964). Of the five types of cement, Type I is the most widely used in ground-water related work.

Portland cement mixed with water in the above-cited proportions creates slurry that weighs approximately 14 to 15 pounds per gallon. A typical 14 pounds per gallon neat cement slurry has a mixed volume of approximately 1.5 cubic feet per sack and a set volume of approximately 1.2 cubic feet; volumetric shrinkage is approximately 17 percent and the porosity of the set cement approximates 54 percent (Moehrl, 1964). The setting time for such a cement mixture ranges from 48 to 72 hours depending primarily on water content. A variety of additives may be mixed with the cement slurry to change the properties of the cement. The more common additives and associated effects on the cement include:

1) bentonite (2 percent to 6 percent). Bentonite improves the workability of the cement slurry, reduces the slurry weight and density, reduces shrinkage as the cement sets and produces a lower unit cost sealing material. Bentonite also reduces the set strength of the seal, but this is rarely a problem because the seal is seldom subject to high stress (Ahrens, 1970);
2) calcium chloride (1 percent to 3 percent). Calcium chloride accelerates the setting time and creates a higher early strength; these attributes are particularly useful in cold climates. Calcium chloride also aids in reducing the amount of slurry that enters into zones of coarse material;
3) gypsum (3 percent to 6 percent). Gypsum produces a quick-setting, very hard cement that expands upon setting. However, the high cost of gypsum as an additive limits the use to special operations;
4) aluminum powder (less than 1 percent). Aluminum produces a strong, quick-setting cement that expands on setting and therefore provides a tighter seal (Ahrens, 1970);
5) fly ash (10 percent to 20 percent). Fly ash increases sulfate resistance and early compressive strength;
6) hydroxylated carboxylic acid. Hydroxylated carboxylic acid retards setting time and improves

workability without compromising set strength; and

7) diatomaceous earth. Diatomaceous earth reduces slurry density, increases water demand and thickening time and reduces set strength.

Water used to mix neat cement should be clean, fresh water free of oil or other organic material and the total dissolved mineral content should be less than 2000 parts per million. A high sulfate content is particularly undesirable (Campbell and Lehr, 1975). If too much water is used, the grout will be weakened and excessive shrinkage will occur upon setting. If this occurs, the annulus will not be completely filled after the grouting operation. The voids in the annulus may not be seen from the surface but may still be present along the length of the casing (Kurt, 1983).

Mixing of neat cement grout can be accomplished manually or with a mechanical mixer. Mixing must be continuous so that the slurry can be emplaced without interruption. The grout should be mixed to a relatively stiff consistency and immediately pumped into the annulus. The types of pumps suggested for use with grout include reciprocating (piston) pumps, diaphragm pumps, centrifugal pumps or moyno-type pumps. These pumps are all commonly used by well drilling contractors.

Neat cement, because of its chemical nature (calcium carbonate, alumina, silica, magnesia, ferric oxide and sulfur trioxide), is a highly alkaline substance with a pH that typically ranges from 10 to 12. This high pH presents the potential for alteration of the pH of water with which it comes in contact. This alteration of pH in the ground water can subsequently affect the representativeness of any water-quality samples collected from the well. Because the mixture is emplaced as a slurry, the coarse materials that comprise the filter pack around the intake portion of a monitoring well may be infiltrated by the cement if the cement is placed directly on top of the filter pack. This is particularly true of thinner slurries that are mixed with more than 6 gallons of water per sack of cement. The cement infiltration problem also can be aggravated if well development is attempted prior to the time at which the cement has reached final set.

These problems can have a severe and persistent effect on the performance of the monitoring well in terms of yield and sample integrity. If thin grout is placed on top of the filter pack and infiltrates, the cement material can plug the filter pack and/or the well intake upon setting. The presence of the high-pH cement within the filter pack can cause anomalous pH readings in subsequent water samples taken from the well. Dunbar et al. (1985) reported that wells completed in low-permeability geologic materials with cement placed on top of the filter pack consistently produced samples with a pH greater than 9 for two and one-half years despite repeated attempts at well development. For these reasons, neat cement should not be emplaced directly on top of the filter pack of a monitoring well. Ramsey and Maddox (1982) have suggested that a 1 to 2-foot thick very fine-grained sand layer be placed atop the filter pack material prior to emplacement of the neat cement grout to eliminate the grout infiltration potential. A 2- to 5-foot thick bentonite seal will accomplish the same purpose, but requires additional time to allow the bentonite to hydrate prior to cement placement. Either or both of these procedures serve to minimize well performance impairment and chemical interference effects caused by the proximity of neat cement to the well intake.

Another potential problem with the use of neat cement as an annular sealing material centers around the heat generated by the cement as it sets. When water is mixed with any type of Portland cement, a series of spontaneous chemical hydration reactions occur. If allowed to continue to completion, these reactions transform the cement slurry into a rigid solid material. As the hydration reactions progress and the cement cures, heat is given off as a by-product; this heat is known as the heat of hydration (Troxell et al., 1968). The rate of dissipation of the heat of hydration is a function of curing temperature, time, cement chemical composition and the presence of chemical additives (Lerch and Ford, 1948). Generally, the heat of hydration is of little concern. However, if large volumes of cement are used or if the heat is not readily dissipated (as it is not in a borehole because of the insulating properties of geologic materials), relatively large temperature rises may result (Verbeck and Foster, 1950). The high heats can cause the structural integrity of some types of well casing, notably thermoplastic casing, to be compromised. Thermoplastics characteristically lose strength and stiffness as the temperature of the casing increases. Because collapse pressure resistance of a casing is proportional to the material stiffness, if casing temperatures are raised sufficiently this can result in failure of the casing (Johnson et al., 1980).

Molz and Kurt (1979) and Johnson et al. (1980) studied the heat of hydration problem and concluded:

1) peak casing temperatures increase as the grout thickness increases. Temperature rises for casings surrounded by 1.5 inches to 4-inches of Type I neat cement ranged from 16°F to 45°F; temperature rises for casings surrounded by 12 inches of grout (i.e. where washouts or caving or collapse of formation materials into the borehole might occur) can be in excess of 170 °F. In the former case, plastic pipe retains a large fraction of collapse strength, but in the latter case, some types of plastic pipe lose a large fraction of the collapse strength (Gross, 1970);
2) the ratio of the grout-soil interface surface area to the volume of grout significantly influences peak casing temperatures. Additionally, peak temperature rise for any casing size is nonlinear with respect to grout thickness. Lower peak temperatures can thus be expected for smaller-diameter casings; and
3) peak temperatures are normally reached 8 to 10 hours after water is added to the cement, and casing temperatures remain near their peak for several hours before slowly returning to the original temperature.

The use of setting time accelerators, such as calcium chloride, gypsum or aluminum powder can increase the heat of hydration and cause casings to overheat while the grout is curing. This temperature increase poses an increased potential for casing failure. Both Molz and Kurt (1979) and Johnson et al. (1980) attribute uncommon *premature* collapses of neat *cement* grouted thermoplastic-cased wells to two factors: 1) that most grouting is done by filling the annulus from the bottom upward and 2) that as the grout cures, it gains strength and provides support to the casing.

Several methods can be used to minimize the heat of hydration. Adding setting-time retardants, such as bentonite or diatomaceous earth, to the grout mix tends to reduce peak temperatures. Other approaches include: adding inert materials such as silica sand to the grout; circulating cool water inside the casing during grout curing; and increasing the water-cement ratio of the grout mix (Kurt, 1983). However, increasing the water-cement ratio of the grout mix results in increased shrinkage and decreased strength upon setting and more potential to move beyond where expected or intended before setting.

Neat cement annular seals are subject to channeling between the casing and the seal 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 (Kurt and Johnson, 1982). One method of ensuring a low-permeability grout seal in a monitoring well is to minimize the shrinkage of the grout as it cures. Minimizing shrinkage, lowering permeability and increasing the strength of cured grout can be accomplished by minimizing water/cement ratios (Kurt and Johnson, 1982). Typical vertical permeabilities for casing/grout systems were found by Kurt and Johnson (1982) to range from 20 to 100 x 10^{-5} centimeters per second. These permeabilities are higher than those determined for neat cement grout only. This implies that the presence of casing is a factor that increases the permeability of the system.

Methods for Evaluating Annular Seal Integrity

There are presently no fooproof field tests that can be performed to determine if a proper annular seal has been achieved. Of the most commonly used field tests for checking seals in production wells, only one appears to provide basic information on the integrity of an annular seal in a monitoring well--geophysical logging. The accuracy of geophysical logging techniques is often questioned because they are indirect sensing techniques. The log most commonly used to check a seal composed of neat cement grout is the cement bond (acoustic, sonic) log. A cement bond log generally indicates bonded and non-cemented zones but cannot detect the presence of vertical channels within the cement nor small voids in the contact area with the casing. Cement bond logs are available for wells with inside diameters of 2 inches or larger.

Where thermoplastic or fluorocarbon casing is installed, there is no sound or sonic wave return recorded along the casing as is the case with metallic pipe. As a consequence, the information derived is even more difficult to interpret. Further, there are no good methods available to evaluate the effectiveness of bentonite seals. This is an area in need of further research.

Surface Completion and Protective Measures

Two types of surface completions are common for ground-water monitoring wells: 1) above-ground completion and 2) flush-to-ground surface completion. An above-ground completion is preferred whenever practical, but a flush-to-ground surface may be required at some sites. The primary purposes of either type of completion are to prevent surface runoff from entering and infiltrating down the annulus of the well and to protect the well from accidental damage or vandalism.

Surface Seals

Whichever type of completion is selected for a well, there should always be a surface seal of neat cement or concrete surrounding the well casing and filling the annular space between the casing and the borehole at the surface. The surface seal may be an extension of the annular seal installed above the filter pack or it may be a separate seal emplaced on top of the annular seal. Because the annular space near the land surface is large and the surface material adjacent to the borehole is disturbed by drilling activity, the surface seal will generally extend to at least 3 feet away from the well casing at the surface; the seal will usually taper down to the size of the borehole within a few feet of the surface. In climates with alternating freezing and thawing conditions, the cement surface must extend below the frost depth to prevent potential well damage caused by frost heaving. A suggested design for dealing with heaving conditions is shown in Figure 21. If cement is mounded around the well to help prevent surface runoff from ponding and entering around the casing, the mound should be limited in size and slope so that access to the well is not: impaired and to avoid frost heave damage. In some states, well installation regulations were initially developed for water supply wells. These standards are sometimes now applied to monitoring wells, and these may require that the cement surface seal extend to depths of 10 feet or greater to ensure sanitary protection of the well.

Above-Ground Completions

In an above-ground completion, a protective casing is generally installed around the well casing by placing the protective casing into the cement surface seal while it is still wet and uncured. The protective casing discourages unauthorized entry into the well, prevents damage by contact with vehicles and protects PVC casing from degradation caused by direct exposure to sunlight. This protective casing should be cleaned thoroughly prior to installation to ensure that it is free of any chemicals or coatings. The protective casing should have a large enough inside diameter to allow easy access to the well casing and to allow easy removal of the casing cap. The protective casing should be fitted with a locking cap and installed so that there is at least 1 to 2 inches clearance between the top of the in-place inner well casing cap and the bottom of the protective casing locking cap when in the locked position. The protective casing should be positioned and maintained in a plumb position. The protective casing should be anchored below frost depth into the cement surface seal and extend at least 18 inches above the surface of the ground.

Like the inner well casing, the outer protective casing should be vented near the top to prevent the accumulation and entrapment of potentially explosive gases and to allow water levels in the well to respond naturally to barometric pressure changes. Additionally, the outer protective casing should have a drain hole installed just above the top of the cement level in the space between the protective casing and the well casing (Figure 21). This drain allows trapped water to drain away from the casing. This drain is particularly critical in freezing climates where freezing of water trapped between the inner well casing and the outer protective casing can cause the inner casing to buckle or fail.

A case-hardened steel lock is generally installed on the locking casing cap to provide well security. However, corrosion and jamming of the locking mechanism frequently occurs as the lock is exposed to the elements. Lubricating the locks or the corroded locking mechanisms is not recommended because lubricants such as graphite, petroleum-based sprays, silicone and others may provide the potential for sample chemical alteration. Rather, the use of some type of protective measure to shield the lock from the elements such as a plastic covering may prove a better alternative.

In high-traffic areas such as parking lots, or in areas where heavy equipment may be working, additional protection such as the installation of three or more "bumperguards" are suggested. Bumperguards are brightly-painted posts of wood, steel or some other durable material set in cement and located within 3 or 4 feet from the well.

Flush-to-Ground Surface Completions

In a flush-to-ground surface completion, a protective structure such as a utility vault or meter box is installed around well casing that has been cut off below grade. The protective structure is typically set into the cement surface seal before it has cured. This type of completion is generally used in high-traffic areas such as streets, parking lots and service stations where an above-ground completion would severely disrupt traffic patterns or in areas where it is required by municipal easements or similar restraints. Because of the potential for surface runoff to enter the below-grade protective structure and/or well, this type of completion must be carefully designed and installed. For example, the bond between the cement surface seal and the protective structure as well as the seal between the protective structure and removable cover must be watertight. Use of an expanding cement that bonds tightly to the protective structure is suggested. Installation of a flexible o-ring or gasket at the point where the cover fits over the protective structure usually suffices to seal the protective structure. In areas where significant amounts of runoff occur, additional safeguards to manage drainage may be necessary to discourage entry of surface runoff.

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Section 6
Completion of Monitoring Wells

Introduction

Once a borehole has been completed to the desired monitoring depth, the monitoring well must be properly installed. Although monitoring wells can be completed in a variety of configurations, successful completion of any monitoring well must incorporate the following objectives:

1) the well completion must permit specific stratigraphic zones to be sampled with complete confidence that the sample obtained is representative of the in-situ water quality;
2) the well completion must permit contaminants with differing physical properties to be sampled. For example, if the contaminant is denser or lighter than water and therefore sinks or floats accordingly, the well completion must allow collection of a representative ground-water sample;
3) the well must be constructed to prevent cross contamination between different zones. Cross contamination can occur if: a) the intake and/or filter pack spans more than one hydraulic unit, b) hydraulic communication between zones occurs along the borehole/grout interface, the casing/grout interface, or through voids in the seal, c) fractures intersect the wellbore, or d) if loosely compacted soils are adjacent to the borehole;
4) the well completion should minimize any disturbance created during the drilling process. For example, if the well was drilled by hollow-stem augers, the completion techniques should eliminate the void space created by the withdrawal of the augers; and
5) the well completion method should be cost effective; sample integrity, of course, is of critical importance.

To achieve these objectives, the well intake, filter pack, and annular seal must be installed using appropriate techniques. The following discussion addresses these techniques.

Well Completion Techniques

Well Intake Installation

In cohesive unconsolidated material or consolidated formations, well intakes are installed as an integral part of the casing string by lowering the entire unit into the open borehole and placing the well intake opposite the interval to be monitored. Centralizing devices are typically used to center the casing and intake in the borehole to allow uniform installation of the filter pack material around the well intake. If the borehole has been drilled by a technique that creates borehole damage, it is necessary to develop the borehole wall. When the formation is sufficiently stable, this development should be undertaken prior to setting the well intake. After the filter pack has been installed, it is very difficult to clean fractures or to remove mudcake deposits that have been formed on the borehole wall. If the borehole was drilled with the mud rotary technique, the borehole should be conditioned and the wallcake removed from the borehole wall with clean water prior to the installation of the well intake, if possible. An additional discussion on well development is found in Section 7, entitled "Monitoring Well Development."

In non-cohesive, unconsolidated materials when the borehole is drilled by a drill-through casing advancement method, such as a casing hammer or a cable tool technique, the well intake should be centered inside the casing at the end of the riser pipe and held firmly in place as the casing is pulled back. When the well intake is being completed as a natural pack, the outside diameter of the well intake should be between 1 and 2 inches smaller than the outside diameter of the casing that is being retracted. If an artificial filter pack is installed, the outside diameter of the well intake should be at least 3 to 5 inches smaller than the outside diameter of the casing that is being retracted. During artificial filter pack installation, the filter pack material must be maintained above the lower-most level of the casing as the casing is removed. This means that the filter pack is being emplaced continually during the time that the casing is being pulled back and the well intake is being exposed. This procedure minimizes the development of excessive void space adjacent to the well intake as the casing is pulled back.

When the casing is installed through the hollow stem of a hollow-stem auger, an artificial filter pack generally should be emplaced because of the disparity between the outside diameter of the auger flights and the usual 2-inch or 4-inch outside diameter of the casing and well intake that are being installed within the auger flights. If the augers are withdrawn and the formation allowed to collapse around the well intake without installing an artificial filter pack to stabilize the borehole wall, the materials that are adjacent to the well intake may be loose and poorly compacted. Excessive void space adjacent to the well intake can provide an avenue for cross contamination or migration of contaminants. This void or loosely-compacted zone may also interfere with the placement of proper seals.

Loosely-compacted material is difficult to adequately develop from within a small-diameter borehole. The surging methods that are available generally cannot recompact the materials adjacent to the well intake to prevent bentonite or cement grout from migrating downward into the screened zone.

Additionally, where collapse is permitted, the collapsed zone around the well intake is highly disturbed and is no longer stratified similar to the stratification of the natural formation. As a consequence, there will be mixing of horizontal zones, and the possibility exists that chemical changes can be induced by the changes in the physical environment.

Where wells are installed in unconsolidated material by the dual-wall reverse-circulation method, the well casing and well intake are installed through the bit. The only option for completion with this construction method is to allow the materials to collapse around the screen. In this instance, a greater sustained effort is suggested in well-development procedures than is normally required.

Filter Pack Installation

Several methods of emplacing artificial filter packs in the annular space of a monitoring well are available, including: 1) gravity (free fall), 2) tremie pipe, 3) reverse circulation, and 4) backwashing. The last two methods involve the addition of clean water to the filter pack material during emplacement. This addition of fluid can cause chemical alteration of the environment adjacent to the well and pose long-term questions about the representativeness of water samples collected from the well. As with other phases of monitoring well construction, fluids (clean) should only be added when no other practicable method exists for proper filter pack emplacement. An additional discussion on choosing filter pack material size can be found in the section entitled "Artificially Filter-Packed Wells."

Placement of filter packs by gravity or free fall can be successfully accomplished only in relatively shallow wells where the probability of bridging or segregation of the filter pack material is minimized. Bridging causes unfilled voids in the filter pack and may prevent the filter pack material from reaching the intended depth. Segregation of filter pack material can result in a well that consistently produces sediment-laden water samples. Segregation is a problem particularly in wells with a shallow static water level. In this situation, the filter pack material falls through the column of water at different rates. The greater drag exerted on smaller particles due to their greater surface area-to-weight ratio causes finer grains to fall at a slower rate than coarser grains. Thus, coarser materials will comprise the lower portion of the filter pack and finer materials will constitute the upper part (Figure 64). Segregation may not be a problem when emplacing truly uniform filter packs where the uniformity coefficient is less than 2.5, but placement by free fall is not recommended in any other situation (Driscoll, 1986).

With the tremie pipe emplacement method, the filter pack material is introduced through a rigid tube or pipe via gravity directly into the interval adjacent to the well intake (Figure 65). Initially, the end of the pipe is positioned at the bottom of the well intake/borehole annulus. The filter pack material is then poured down the tremie pipe and the tremie is raised periodically to allow the filter pack material to fill the annular space around the well intake. The minimum diameter of a tube used for a tremie pipe is generally 1 1/2 inches; larger-diameter pipes are advisable for filter pack materials that are coarse-grained or characterized by uniformity coefficients that exceed 2.5 (California Department of Health Services, 1986). When installing a filter pack with a uniformity coefficient greater than 2.5 in wells deeper than 250 feet, a variation of the standard tremie

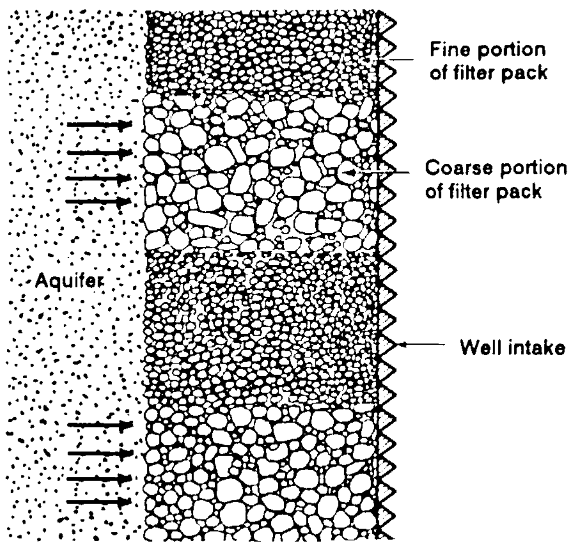

Figure 64. Segregation of artificial filter pack materials caused by gravity emplacement.

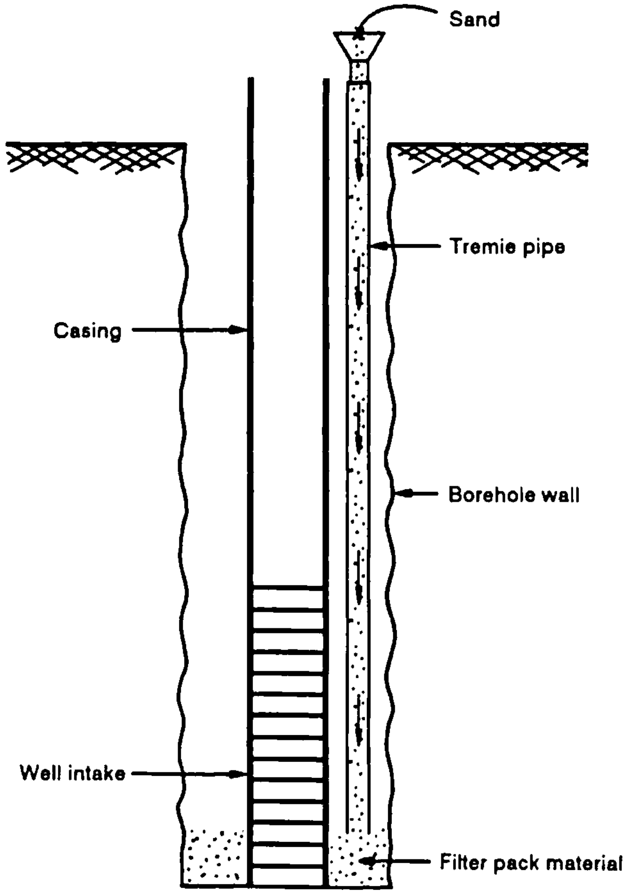

Figure 65. Tremie-pipe emplacement of artificial filter pack materials.

method that employs a pump to pressure feed the materials into the annulus is suggested by the California Department of Health Services (1986).

In the reverse circulation method, a filter pack material and water mixture is fed into the annulus around the well intake. Return flow of water passes into the well intake and is then pumped to the surface through the riser pipe/casing (Figure 66). The filter pack material should be introduced into the annulus at moderate rate to allow for an even distribution of material around the well intake. Care must be exercised when pulling the outer casing so that the riser pipe is not also pulled.

Backwashing filter pack material into place is accomplished by allowing filter pack material with a uniformity coefficient of 2.5 or less to fall freely through the annulus while concurrently pumping clean fresh water down the casing, through the well intake and back up the annulus (Figure 67). Backwashing is a particularly effective method of filter-pack emplacement in cohesive, non-caving geologic materials. This method also minimizes the formation of voids that tend to occur in tremie pipe emplacement of the filter pack.

Annular Seal Installation

The two principal materials used for annular seals are bentonite and neat cement. Often a combination of the two materials is used. Because the integrity of ground-water samples depends on good seals, the proper emplacement of these seals

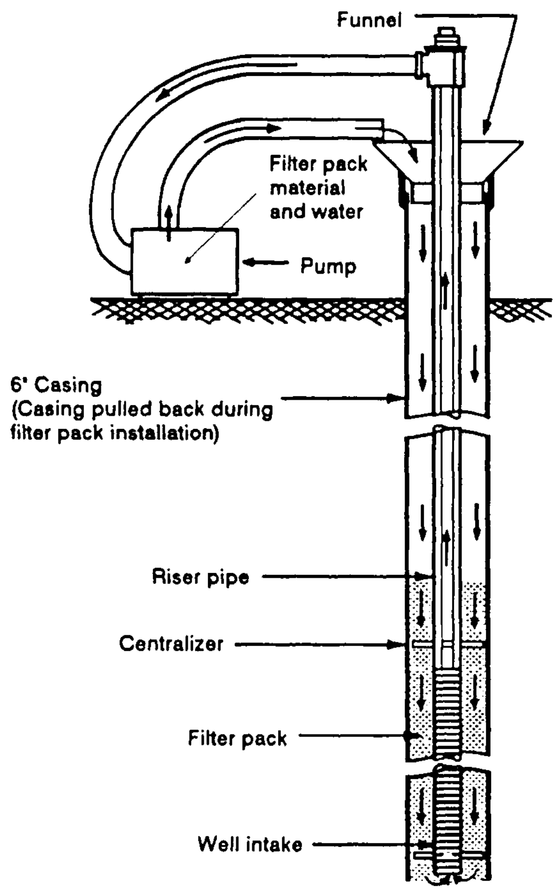

Figure 66. Reverse-circulation emplacement of artificial filter pack materials.

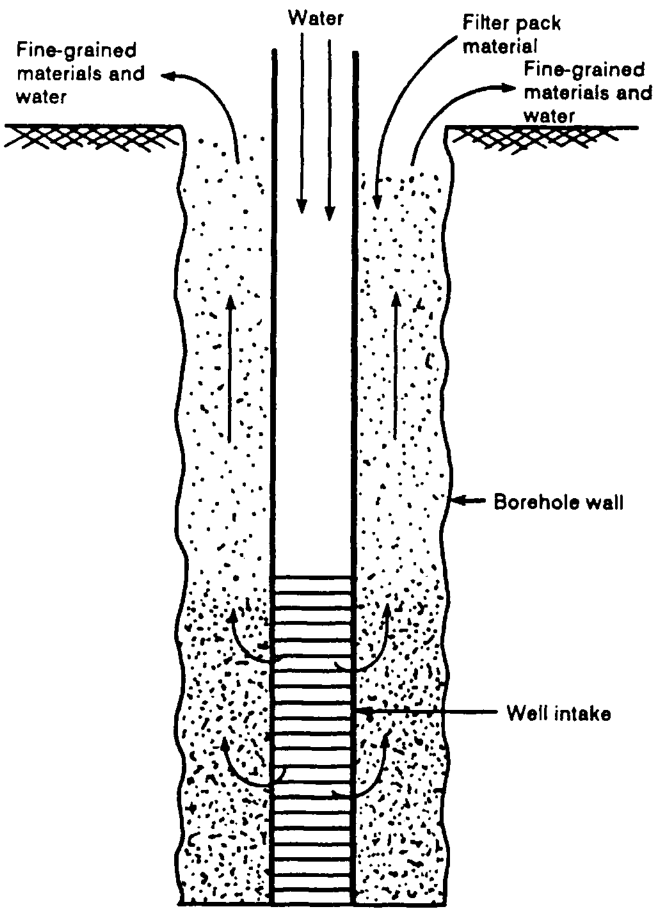

Figure 67. Emplacement of artificial filter pack material by backwashing.

is paramount. An additional discussion on annular seals can be found in the section entitled "Annular Seals."

Bentonite —

Bentonite may be emplaced as an annular seal in either of two different forms: 1) as a dry solid or 2) as a slurry. Typically only pelletized or granular bentonite is emplaced dry; powdered bentonite is usually mixed with water at the surface to form a slurry and then is added to the casing/borehole annulus. Additional discussion on properties of bentonite can be found in Chapter 5 in the section entitled "Materials Used For Annular Seals."

Dry granular bentonite or bentonite pellets may be emplaced by the gravity (free fall) method by pouring from the ground surface. This procedure should only be used in relatively shallow monitoring wells that are less than 30 feet deep with an annular space of 3 inches or greater. When the gravity method is used, the bentonite should be tamped with a tamping rod after it has been emplaced to ensure that no bridging of the pellets or granules has occurred. Where significant thicknesses of bentonite are added, tamping should be done at selected intervals during the emplacement process. In deeper wells, particularly where static water levels are shallow, emplacing dry bentonite dilution of the slurry and the bridging of the mixture with upper formation material.

In pressure grouting, the cement discharges at the bottom the annular space and flows upward around the inner casing until the annular space is completely filled. A side discharge tremie may be used to lessen the possibility that grout might be forced into the filter pack. Depending on pressure requirements, the tremie pipe may be moved upward as the slurry is emplaced or it may be left at the bottom of the annulus until the grouting is completed. If the tremie pipe is not retracted while grouting, the tremie pipe should be removed immediately afterward to avoid the possibility of the grout setting around the pipe. If this occurs, the pipe may be difficult to remove and/or a channel may develop in the grout as the pipe is removed.

In gravity emplacement, the tremie is lowered to the bottom of the annular space and filled with cement. The tremie pipe is slowly retracted, and the weight of the column forces the cement into the annular space. In both gravity emplacement and pressure grouting, the discharge end of the tremie pipe should remain submerged at least one foot below the surface of the grout at all times during emplacement, and the pipe should be kept full of grout without air space. To avoid the formation of cold joints, the grout should be emplaced in one continuous pour before initial setting of the cement or before the mixture loses fluidity. Curing time required for a typical Type I Portland cement to reach maximum strength is a minimum of 40 hours.

Moehrl (1964) recommends checking the buoyancy force on the casing during cementing with grout. Archimede's principle states that a body wholly or partially immersed in a fluid buoyed up by a force equal to the weight of the fluid displaced the body. Failure to recognize this fact may result in unnoticed upward displacement of the casing during cementing. This is particularly true of lighter thermoplastic well casings. Formulas for computing buoyancy are provided by Moehrl (1964).

Types of Well Completions

The ultimate configuration of a monitoring well is chosen to fulfill specific objectives as stated at the beginning of this section. Monitoring wells can be completed either as single wells screened in either short or long intervals, single wells screened in multiple zones or multiple wells completed at different intervals in one borehole. The decision as to which type of monitoring well configuration to install in a specific location is based on cost coupled with technical considerations and practicality of installation.

In shallow installations, it generally is more economical to complete the monitoring wells as individual units that are in close proximity to each other and avoid the complexity of multiple-zone completions in a single borehole. In deeper installations where the cost of drilling is high relative to the cost of the materials in the well and where cost savings can be realized in improved sampling procedures, it may be better to install a more sophisticated multilevel sampling device. The cost of these completions are highly variable depending on the specific requirements of the job. Cost comparisons should be de on a site-by-site basis. Individual well completions will ost always be more economical at depths of less than 80 feet. A discussion of the types of monitoring well completions is presented below.

Single-Riser/Limited-Interval Wells

The majority of monitoring wells that are installed at the present time are individual monitoring wells screened in a specific zone. Well intakes are usually moderate in length, ranging from 3 to 10 feet. These wells are individually installed in a single borehole with a vertical riser extending from the well intake to the surface. Because the screened interval is short, these are the easiest wells to install and develop. A typical example of this design is shown in Figure 21.

The intent of a well with this design is to isolate a specific zone from which water-quality samples and/or water levels are to be obtained. If the well intake crosses more than one zone of permeability, the water sample that is collected will represent the quality of the more permeable zone. If a pump is installed just above the well intake and the well is discharged at a high rate, the majority of the sample that is obtained will come from the upper portion of the well intake. If the pump is lowered to the mid-section of the well intake and pumped at a low rate, the bulk of the sample will come from the area that is immediately adjacent to the zone of the pump intake. At high pumping rates in both isotropic and stratified formations, flow lines converge toward the pump so that the sample that is obtained is most representative of the ground water moving along the shortest flow lines. If the well is not properly sealed above the well intake, leakage may occur from upper zones into the well intake.

Single-Riser/Flow-Through Wells

Flow-through wells consist of a long well intake that either fully or nearly fully penetrates the aquifer. The well intake is connected to an individual riser that extends to the surface. Wells of this type are typically small in diameter and are designed to permit water in the aquifer to flow through the well in such a manner as to make the well "transparent" in the ground-water flow field. An illustration of this type of well is shown in Figure 69.

This type of well produces water samples that are a composite of the water quality intercepted when the well is surged,

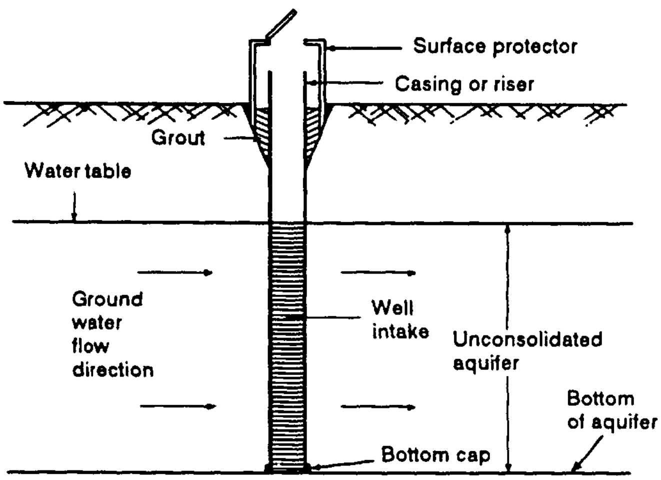

Figure 69. Diagram of a single-riser/flow-through well.

a second seal is placed above the filter pack that is emplaced around the second well intake. If there is a long vertical interval between successive well intakes, neat cement grout is emplaced above the lower seal. Where vertical separation permits, a 1-foot layer of fine silica sand should be emplaced between the filter packs and sealants. This sand helps prevent sealant infiltration into the filter pack and loss of filter pack into the sealant. This procedure is repeated at all desired monitoring intervals. Because each riser extends to the surface and is separate from the other risers, a good seal must be attained around each riser as it penetrates through successive bentonite seals. A substantial problem with this type of construction is leakage along the risers as well as along the borehole wall.

The primary difficulty with multiple completions in a single borehole is that it is difficult to be certain that the seal placed between the screened zones does not provide a conduit that results in interconnection between previously non-connected zones within the borehole. Of particular concern is leakage along the borehole wall and along risers where overlying seals are penetrated. It is often difficult to get an effective seal between the seal (e.g., bentonite or cement grout) and the material of the risers.

Multiple-Level Monitoring Wells

In addition to well nests that sample at multiple levels in a single location, a variety of single-hole, multilevel sampling devices are available. These sampling devices range from the simple field-fabricated, PVC multilevel sampler shown in Figure 71 to the buried capsule devices that are installed in a single borehole, as shown in Figure 72. The completion of these wells is similar to the completion of nested wells in a single borehole. Some of these samplers have individual tubing connections that extend to the surface. Samples are collected from the tubing. With some forms of instrumentation, water levels can also be obtained. There are, additionally, more sophisticated sampling devices available, such as shown in Figure 73. These consist of multiple-zone inflatable packers that can be installed in a relatively small borehole. They permit the sampling of formation fluids at many intervals from within a single borehole. Disadvantages of these devices are: 1) it is difficult, if not impossible, to repair the device if clogging occurs, 2) it is difficult to prevent and/or evaluate sealant and packer leakage and 3) these installations are more expensive than single-level monitoring wells.

Simple vacuum-lift multiple port devices can be used in shallow wells where samples can be obtained from the individual tubing that extends to the surface. With increasing depth, greater sophistication is required and a variety of gas-lift sampling devices are available commercially. Still more sophisticated sampling devices are available for very deep installations. These devices require durable, inflatable packer systems and downhole tools to open and close individual ports to obtain formation pressure readings and take fluid samples. These can be used in wells that are several thousand feet deep.

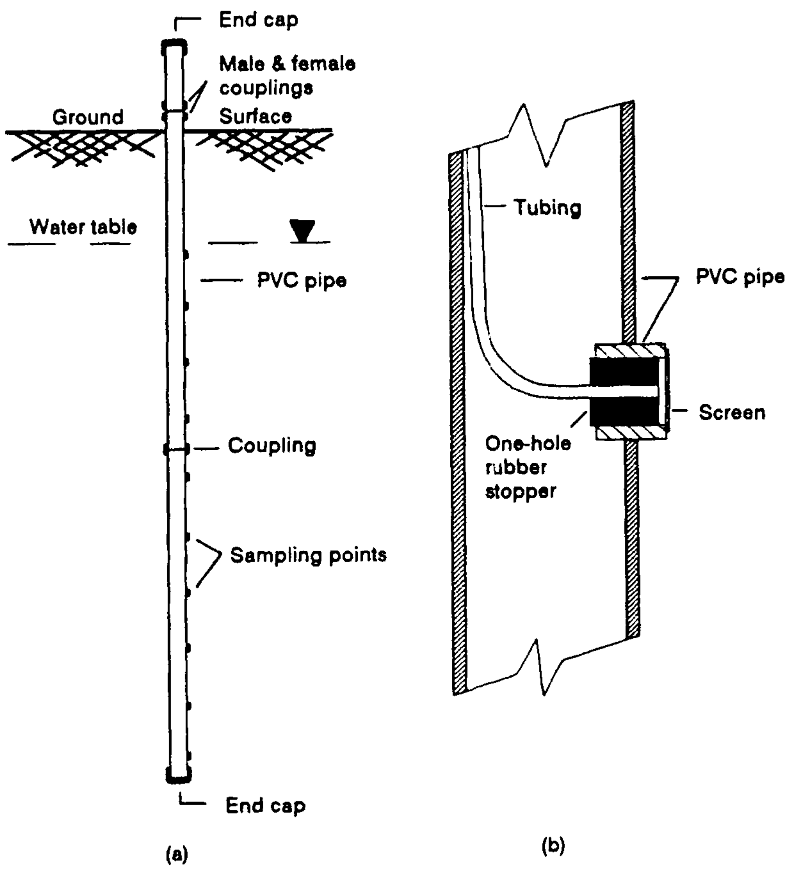

Figure 71. Field-fabricated PVC multilevel sampler: a) field installation and b) cross section of sampling point (Pickens et al., 1981).

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Section 7
Monitoring Well Development

Introduction/Philosophy

The objective of monitoring well development is frequently misconstrued to be merely a process that enhances the flow of ground water from the formation into the well and that minimizes the amount of sediment in the water samples collected from the well. These are the proper objectives for the development of a production well but they do not fulfill the requirements for a monitoring well. A monitoring well should be a "transparent", window into the aquifer from which samples can be collected that are truly representative of the quality of water that is moving through the formation. This objective is difficult to attain and is unattainable in some instances. However, the objective should not be abandoned because of the difficulty.

The interpretation of any ground-water sample collected from a monitoring well should reflect the degree of success that has been reached in the development of the well and the collection of the sample. This objective is frequently overlooked in the literature and in much of the work that has been done in the field. Further research is required before the reliability of samples taken from a monitoring well can be effectively substantiated. The United States Environmental Protection Agency (1986) in the Technical Enforcement Guidance Document (TEGD) states that, "a recommended acceptance/rejection value of five nephelometric turbidity units (NTU) is based on the need to minimize biochemical activity and possible interference with ground-water sample quality." The TEGD also outlines a procedure for determining the source of turbidity and usability of the sample and well. There are instances where minimizing turbidity and/or biochemical activity will result in a sample that is not representative of water that is moving through the ground. If the ground water moving through the formation is, in fact, turbid, or if there is free product moving through the formation, then some criteria may cause a well to be constructed such that the actual contaminant that the well was installed to monitor will be filtered out of the water. Therefore, it is imperative that the design, construction and development of a monitoring well be consistent with the objective of obtaining a sample that is representative of conditions in the ground. An evaluation of the degree of success in attaining this objective should always be included and considered in conjunction with the laboratory and analytical work that is the final result of the ground-water sample-collection process.

If the ultimate objective of a monitoring well is to provide a representative sample of water as it exists in the formation, then the immediate objective and challenge of the development program is to restore the area adjacent to the well to its indigenous condition by correcting damage done to the formation during the drilling process. This damage may occur in many forms: 1) if a vibratory method such as driving casing is used during the drilling process, damage may be caused by compaction of the sediment in place; 2) if a compacted sand and gravel is drilled by a hollow-stem auger and then allowed to collapse around the monitoring well intake, damage may be the resultant loss of density of the natural formation; 3) if a drilling fluid of any type is added during the drilling process, damage may occur by the infiltration of filtrate into the formation; and 4) if mud rotary, casing driving or augering techniques are used during drilling, damage may be caused by the formation of a mudcake or similar deposit that is caused by the drilling process. Other formation damage may be related to specific installations. Some of this damage cannot be overcome satisfactorily by the current capability to design and develop a monitoring well. One important factor is the loss of stratification in the monitored zone. Most natural formations are stratified; the most common stratigraphic orientation is horizontal. The rate of water movement through different stratigraphic horizons varies; sorption rates may differ as stratigraphy changes; and chemical interaction between contaminants and the formation materials and ground water can vary between different horizons. During the development process, those zones with the highest permeability will be most affected by the development of the well. Where a well intake crosses stratigraphic boundaries of varying permeability, the water that moves into and out of the well intake will be moving almost exclusively into and out of the high permeability zones.

Factors Affecting Monitoring Well Development

There are three primary factors that influence the development of a monitoring well: 1) the type of geologic material, 2) the design and completion of the well and 3) the type of drilling technology employed in the well construction. From these factors it is also possible to estimate the level of effort required during development so that the monitoring well will perform satisfactorily.

Type of Geologic Material

The primary geologic consideration is whether or not the monitoring well intake will be installed in consolidated rock or unconsolidated material. If the intake is installed in consolidated rock or cohesive unconsolidated material, the assumption can often be made that the borehole is stable and was stable during the construction of the monitoring well. In a stable borehole, it is generally easier to: 1) install the well intake(s) at the prescribed setting(s), 2) uniformly distribute and maintain the proper height of a filter pack (if one was installed) above the well intake(s), 3) place the bentonite seal(s) in the intended

Well Development

Very little research has been performed that specifically addresses movement of fluid, with or without contaminants present, through a stratified aquifer into monitoring wells. Ground-water flow theory is based on the primary assumptions of homogeneity and isotropism of the formation. In production wells, these assumptions are acceptable because the aquifer is stressed over a sufficient area for variations to be "averaged." Most discussions of monitoring-well flow characteristics are based on the acceptance of these assumptions. However, these are not always valid assumptions for attaining the objectives of monitoring wells.

Where it is intended to intercept a contaminant in a restricted zone of a three-dimensional flow field, a monitoring well must be installed and developed with a much greater precision than is normal for production wells. The relative movement of fluid in specific zones becomes significantly more important than the gross yield. Both installation and development must be performed with a "spot precision" that preserves in situ conditions and permits the collection of a representative sample.

The methods that are available for the development of monitoring wells have been inherited from production well development practices. These methods include: 1) surging with a surge block, 2) bailing, 3) pumping, overpumping and backwashing through the pump, 4) airlift pumping and 5) air surging and jetting. A number of authors have written about these available methods of development for monitoring wells. A summary of these articles is contained in Table 36.

Based on a review of the literature and on a wide range of actual field practices, a few generalizations about development of monitoring wells can be made:

1) using air for well development can result in chemical alteration of the ground water both as a result of chemical reaction with the air and as a result of impurities introduced through the air stream;
2) adding water to the borehole for stabilization, surging, backwashing, flushing or any other purpose has an unpredictable effect on ground-water quality and at the very least causes dilution. Even if the water added to the borehole was originally pumped from the same formation, chemical alteration of the ground water in the formation can occur if the water is reinjected. Once water has been pumped to the surface, aeration can alter the original water quality;
3) developing the formation at the interface between the outer perimeter of an artificial filter pack and the inner perimeter of the borehole is extremely difficult. Any mudcake or natural clay deposited at this interface is very difficult to remove; incomplete removal can have unquantifiable short- and long-range impacts on the quality of the sampled ground water;
4) developing a well is relatively easy when the well intake is placed in a clean homogenous aquifer of relatively high permeability. It is very difficult to develop a representative well in an aquifer that is stratified, slowly permeable and fine-grained, particularly where there is substantial variation between the various stratified zones;
5) developing a larger-diameter monitoring well is easier than developing a smaller-diameter well. This is particularly true if the development is accomplished by overpumping or backwashing through the pump because suitable pumping capacity is not commonly available for small-diameter wells with deep static water levels. However, a smaller-diameter well is more "transparent" in the aquifer flow field and is therefore more likely to yield a representative sample;
6) collecting a non-turbid sample may not be possible because there are monitoring wells that cannot be sufficiently developed by any available technique. This may be the consequence of the existence of turbid water in the formation or the inability to design and construct a well that will yield water in satisfactory quantity without exceeding acceptable flow velocities in the natural formation;
7) applying many of the monitoring well-development techniques in small-diameter (2-inch) wells and using the design and construction techniques discussed in the literature are easiest in shallow monitoring situations with good hydraulic conductivity. These techniques may be impractical when applied to deeper or more difficult monitoring situations.
8) Adding clean water of known quality for flushing and/or jetting should be done only when no better options are available. A record must be kept of the quantities of water lost to the formation during the flushing/jetting operation and every attempt must be made to reestablish background levels in a manner similar to that described in Barcelona et al. (1985a) and/or the United States Environmental Protection Agency (1986); and
9) dealing objectively with the conditions and problems that exist for every installation is essential. The problems encountered at each site should be addressed and clearly presented in the final report. Chemical analyses must be included in the final report so that anyone evaluating these analyses is able to understand the limitations of the work.

Methods of Well Development

Monitoring well development is an attempt to remove fine particulate matter, commonly clay and silt, from the geologic formation near the well intake. If particulate matter is not removed, as water moves through the formation into the well, the water sampled will be turbid, and the viability of the water quality analyses will be impaired. When pumping during well development, the movement of water is unidirectional toward the well. Therefore, there is a tendency for the particles moving toward the well to "bridge" together or form blockages that restrict subsequent particulate movement. These blockages may prevent the complete development of the well capacity. This effect potentially impacts the quality of the water discharged. Development techniques should remove such bridges

Table 36. (Continued)

Reference	Overpumping	Backwashing	Surge Block*	Bailer	Jetting	Airlift Pumping	Air Surging
Everett (1980)	Development operation must cause flow reversal to avoid bridging; can alternate pump off and on		Suitable; periodic bailing to remove fines		High velocity jets of water generally most effective; discret zones of development		
Keely and Boateng (1987 a and b)	Probably most desirable when surged; second series of evacuation/ recovery cycles is recommended after resting the well for 24 hours; settlement and loosening of fines ocurs after the first development attempt; not as vigorous as backwashing	Vigorous surging action may not be desirable due to disturbance of gravel pack	Method quite effective in loosening fines but may be inadvisable in that filter pack and fluids may be displaced to degree that damages value as a filtering media		Popular but less desirable; method different from water wells; water displaced by short downward bursts of high-pressure injection; important not to jet air or water across screen because fines driven into screen cause irreversible blockage; may substantially displace native fluids	Air can become entrained behind screen and reduce permeability	

* Schalla and Landick (1986) report on special 2"- valved block

** For low hydraulic conductivity wells, flush water up annulus prior to sealing; afterwards pump

There are a variety of dart valve, flat bottom and sand pump bailers available for the development of larger-diameter wells. These bailers are typically fabricated from steel and are operated by using a specially designated line on the rig. For most monitoring-well applications, small-diameter PVC or fluoropolymer bailers are readily available. When commercial bailers are not available, bailers can be fabricated from readily available materials. Bailers of appropriate diameter, length, material and weight should be used to avoid potential breakage of the well casing or screen. Figures 74a and 74b show a schematic representation of typical commercially available small-diameter bailers.

Surge Block

Surge blocks, such as are shown in Figures 75 and 76, can be used effectively to destroy bridging and to create the agitation that is necessary to develop a well. A surge block is used alternately with either a bailer or pump so that material that has been agitated and loosened by the surging action is removed. The cycle of surging-pumping/bailing is repeated until satisfactory development has been attained.

During the development process, the surge block can be operated either as an integral part of the drill rods or on a wireline. In either event, the surge block assembly must be of sufficient weight to free-fall through the water in the borehole and create a vigorous outward surge. The equipment that lifts or extracts the surge block after the downward plunge must be strong enough to pull the surge block upward relatively rapidly. The surge block by design permits some of the fluid to bypass on the downward stroke, either around the perimeter of the surge block or through bypass valves.

The surge block is lowered to the top of the well intake and then operated in a pumping action with a typical stroke of approximately 3 feet. The surging is usually initiated at the top of the well intake and gradually is worked downward through the screened interval. The surge block is removed at regular intervals and the fine material that has been loosened is removed by bailing and/or pumping. Surging begins at the top of the well intake so that sand or silt loosened by the initial surging action cannot cascade down on top of the surge block and prevent removal of the surge block from the well. Surging is initially gentle, and the energy of the action is gradually increased during the development process. The vigor of the surging action is controlled by the speed, length and stroke of the fall and speed of retraction of the surge block. By controlling these rates, the surging activity can range from very rigorous to very gentle.

Surging within the well intake can result in serious difficulties. Vigorous surging in a well that is designed such that excessive sand can be produced, can result in sand-locking the surge block. This should not occur in a properly designed monitoring well, nor should it occur if the surge block of appropriate diameter is properly used. As in the case of bailer surging, if excessive force is used, it is possible to cause the collapse of the well intake and/or the casing.

An alternative to surging within the well intake is to perform the surging within the casing above the well intake. This has the advantage of minimizing the risk of sand locking. However, it also reduces the effectiveness of the surging action. In permeable material, the procedure of surging above the well intake is effective only for well intakes with lengths of 5 feet or less.

If the well is properly designed, and if: 1) the surge block is initially operated with short, gentle strokes above the well intake, 2) sand is removed periodically by alternating sand removal with surging, 3) the energy of surging is gradually increased at each depth of surging until no more sand is produced from surging at that depth, and 4) the depth of surging is incrementally increased from top to bottom of the well intake, then surging can be conducted effectively and safely.

Where there is sufficient annular space available within the casing, which is seldom the case with monitoring wells, it is effective to install a low-capacity pump above the surge block. By discharging from the well concurrent with surging, a gradient is maintained toward the well. This set-up assists in developing the adjacent aquifer by maintaining the movement of particulate material toward the well.

Surging is usually most effective when performed by cable tool-type machines. The hydraulic hoisting equipment that is normally available on most other types of drilling equipment does not operate with sufficient speed to provide high-energy surging. Where properly used, the surge block in combination with bailing or pumping may be the most effective form of mechanical development.

Pumping/Overpumping/ Backwashing

The easiest, least-expensive and most commonly employed technique of monitoring-well development is some form of pumping. By installing a pump in the well and starting the pump, ground-water flow is induced toward the well. Fine-particulate material that moves into the well is discharged by the pump. In overpumping, the pump is operated at a capacity that substantially exceeds the ability of the formation to deliver water. This flow velocity into the well usually exceeds the flow velocity that will subsequently be induced during the sampling process. This increased velocity causes rapid and effective migration of particulates toward the pumping well and enhances the development process. Proper design is needed to avoid well collapse, especially in deep wells. Both pumping and overpumping are easily used in the development of a well.

Where there is no backflow-prevention valve installed, the pump can be alternately started and stopped. This starting and stopping allows the column of water that is initially picked up by the pump to be alternately dropped and raised up in a surging action. Each time the water column falls back into the well, an outward surge of water flows into the formation. This surge tends to loosen the bridging of the fine particles so that the upward motion of the column of water can move the particles into and out of the well. In this manner, the well can be pumped, overpumped and back-flushed alternately until such time as satisfactory development has been attained.

While the preceding procedures can effectively develop a well, and have been used for many years in the development of production wells, pumping equipment suitable to perform these operations may not be available that will fit into some small-diameter monitoring wells. To be effective as a development tool, pumps must have a pumping capability that ranges from

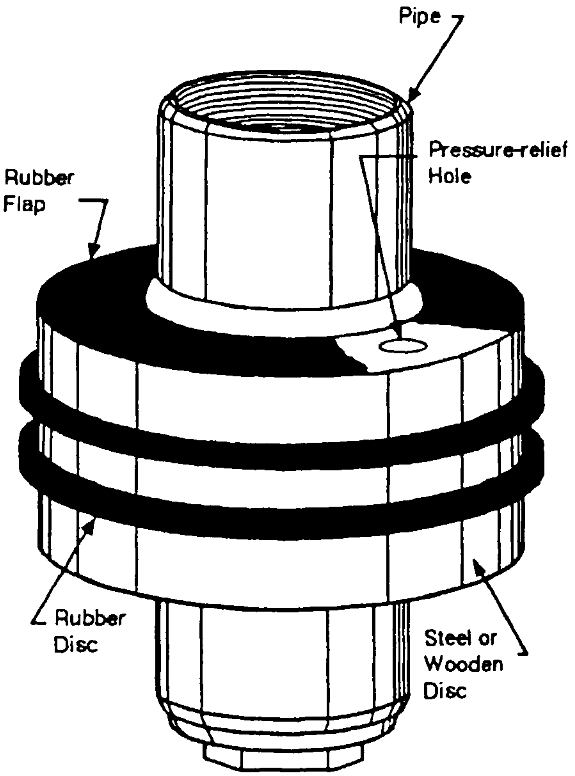

Figure 75. Diagram of a typical surge block (Driscoll, 1986).

very low to very high or be capable of being controlled by valving. The sampling pumps that are presently designed to fit into small-diameter boreholes commonly do not provide the upper range of capacities that often are needed for this type of development. For shallow wells with water levels less than 25 feet deep, a suction-lift centrifugal pump can be used for development in the manner prescribed. The maximum practical suction lift attainable by this method is approximately 25 feet. In practice, bailing or bailing and surging is combined with pumping for the most-efficient well development. The bailing or surging procedures are used to loosen bridges and move material toward the well. A low-capacity sampling pump or bailer is then used to remove turbid water from the well until the quality is satisfactory. This procedure is actually less than completely satisfactory, but is the best-available technology with the equipment that is currently available.

Air lifting, without exposing the formations being developed directly to air, can be accomplished by properly implemented pumping. To do this, the double pipe method of air lifting is preferred. The bottom of the air lift should be lowered to within no more than 10 feet of the top of the well intake, and in no event should the air lift be used within the well intake. If the air lift is used to surge the well, by alternating the air on and off, there will be mixing of aerated water with the water in the ...l. Therefore, if the well is to be pumped by air lifting, the ...on should be one of continuous, regulated discharge. This can be effectively accomplished only in relatively permeable aquifers.

Where monitoring well installations are to be made in formations that have low hydraulic conductivity, none of the preceding well-development methods will be found to be completely satisfactory. Barcelona et al. (1985a) recommend a procedure that is applicable in this situation: "In this type of geologic setting, clean water should be circulated down the well casing, out through the well intake and gravel pack, and up the open borehole prior to placement of the grout or seal in the annulus. Relatively high water velocities can be maintained, and the mudcake from the borehole wall will be broken down effectively and removed. Flow rates should be controlled to prevent floating the gravel pack out of the borehole. Because of the relatively low hydraulic conductivity of geologic materials outside the well, a negligible amount of water will penetrate the formation being monitored. However, immediately following the procedure, the well sealant should be installed and the well pumped to remove as much of the water used in the development process as possible."

All of the techniques described in this section are designed to remove the effects of drilling from the monitored zone and, insofar as possible, to restore the formations penetrated to indigenous conditions. To this end, proposed development techniques, where possible, avoid the use of introduced fluids, including air, into the monitored zone during the development process. This not only minimizes adverse impacts on the quality of water samples, but also restricts development options that would otherwise be available.

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Section 8
Monitoring Well Network Management Considerations

Well Documentation

Records are an integral part of any monitoring system. Comprehensive records should be kept that document data collection at a specific site. These data include boring records, geophysical data, aquifer analysis data, ground-water sampling results and abandonment documentation. Armed with as much data as possible for the site, an effective management strategy for the monitoring well network can be instituted.

Excellent records of monitoring wells must be kept for any management strategy to be effective. Documentation of monitoring well construction and testing must frequently be provided as part of a regulatory program. Many states require drillers to file a well log to document well installation and location. Currently, some states have adopted or are adopting regulations with unique reporting requirements specifically for monitoring wells. At the state and federal level, guidance documents have been developed that address reporting requirements. Tables 37, 38 and 39 illustrate some of the items that ious states have implemented to address monitoring well recordkeeping. Table 40 shows the recommendations of the United States Environmental Protection Agency (1986). An additional discussion on field documentation can be found in the section entitled "Recordkeeping."

The most critical factor in evaluating or reviewing data from a monitoring well is location. If a monitoring well cannot be physically located in the field and/or on a map in relationship to other wells, only limited interpretation of the data is possible. All monitoring wells should be properly located and referenced to a datum. The degree of accuracy for vertical and horizontal control for monitoring well location should be established and held constant for all monitoring wells. In many cases, a licensed surveyor should be contracted to perform the survey of the wells. With few exceptions, vertical elevations should be referenced to mean sea level and be accurate to 0.01 foot (Brownlee, 1985). Because elevations are surveyed during various stages of well/boring installation, careful records must be kept as to where the elevation is established. For example, if ground elevation is determined during the drilling process, no permanent elevation point usually can be established because the ground is disturbed during the drilling process. A temporary pin can be established close to the well location for use in later more accurate measurements, but the completed well must be resurveyed to maintain the desired accuracy of elevation. Each completed well should have a standard surveyed reference point. Because the top of the casing is not always level, quently the highest point on the casing is used. Brownlee (1985) suggests that the standard reference point should be consistent such that the north (or other) side of all monitoring wells is the referenced point. Regardless of what point is chosen, the surveyor should be advised before the survey is conducted and the reference point clearly marked at each well. If paint is used to mark the casing, the paint must not be allowed on the inside of the casing. If spray paint is used, the aerosols can coat the inside of the casing and may cause spurious water-quality results in subsequent samples. An alternative way to mark the casing is to notch the casing so that a permanent reference point is designated. The United States Environmental Protection Agency (1986) recommends that reference marks be placed on both the casing and grout apron.

Well locations should clearly be marked in the field. Each well should have a unique number that is clearly visible on the well or protective casing. To ensure good documentation, the well number may be descriptive of the method used to install the well. For example, a well designated as C-1 could represent the first cored hole, or HS-3 could be a hollow-stem auger hole. If multilevel sampling tubes are being used, each tube should be clearly marked with the appropriate depth interval.

Well locations should be clearly marked on a map. The map should also include roads, buildings, other wells, property boundaries and other reference points. In general, maps illustrating comparable items should be the same scale. In addition to the unique monitoring well number, general well designations may be desirable to include on the map. The Wisconsin Department of Natural Resources (1985) suggests that PIEZ (piezometer), OW (observation well), PVT (private well), LYS (lysimeter) and OTHER be used to clarify the function of the wells.

Files should be kept on each monitoring well so that any suspected problems with the monitoring well can be evaluated based on previous well performance. The accuracy and completeness of the records will influence the ability of the reviewer to make decisions based on historical data.

Well Maintenance and Rehabilitation

The purpose of maintaining a monitoring well is to extend the life of the well and to provide representative levels and samples of the ground water surrounding the well. Maintenance includes proper documentation of factors that can be used as benchmarks for comparison of data at a later point. A scheduled maintenance program should be developed before sample quality is questioned. This section is designed to assist the user in setting up a comprehensive maintenance schedule for a monitoring system.

Documenting Monitoring Well Performance

A monitoring well network should be periodically evaluated to determine that the wells are functioning properly. Once complete construction and "as-built" information is on file for

Table 40. Field Boring Log Information (United States Environmental Protection Agency, 1986)

General:
- Project name
- Hole name/number*
- Date started and finished*
- Geologist's name*
- Driller's name*
- Sheet number
- Hole location; map and elevation*
- Rig type
- Bit size/auger size*
- Petrologic lithologic classification scheme used (Wentworth, unified soil classification system)

Information Columns:
- Depth*
- Sample location/number*
- Blow counts and advance rate
- Percent sample recovery*
- Narrative description*
- Depth to saturation*

Narrative Description:
- Geologic observations:
- soil/rock type*
- color and stain*
- gross petrology*
- friability
- moisture content*
- degree of weathering*
- presence of carbonate*
- fractures*
- solution cavities*
- bedding*
- discontinuities*- e.g., foliation
- water-bearing zones*
- formational strike and dip*
- fossils
- depositional structures*
- organic content*
- odor*
- suspected contaminant*

Drilling Observations:
- loss of circulation
- advance rates*
- rig chatter
- water levels*
- amount of air used, air pressure
- drilling difficulties*
- changes in drilling method or equipment*
- readings from detective equipment, if any*
- amount of water yield or loss during drilling at different depths*
- amounts and types of any liquids used*
- running sands*
- caving/hole stability*

Other Remarks:
- equipment failures
- possible contamination*
- deviations from drilling plan*
- weather

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

show that the performance of the well is deteriorating;

5) Piezometric surface maps should be plotted and reviewed at least annually; and

6) High and low water-level data for each well should be examined at least every 2 years to assure that well locations (horizontally and vertically) remain acceptable. If the water level falls below the top of the well intake, the quality of the water samples collected can be altered.

Where serious problems are indicated with a well(s), geophysical logs may be helpful in diagnosing maintenance needs. Caliper logs provide information on diameter that may be used to evaluate physical changes in the borehole or casing. Gamma logs can be used to evaluate lithologic changes and can be applied to ascertain whether or not well intakes are properly placed. Spontaneous potential logs can locate zones of low permeability where siltation may originate. Resistivity logs identify permeable and/or porous zones to identify formation boundaries. Television and photographic surveys can pinpoint casing problems and well intake failure and/or blockage. When used in combination, geophysical logs may save time and money in identifying problem areas. An additional discussion of the applicability and limitations of geophysical logging tools can be found in the section entitled "Borehole Geophysical Tools and Downhole Cameras."

Factors Contributing to Well Maintenance Needs

The maintenance requirements of a well are influenced by the design of the well and the characteristics of the monitored zones. Water quality, transmissivity, permeability, storage capacity, boundary conditions, stratification, sorting and fracturing all can influence the need for and method(s) of well maintenance. Table 41 lists major aquifer types by ground-water regions and indicates the most prevalent problems with operation of the wells in this type of rock or unconsolidated deposit. Problems with monitoring wells are typically caused by poor well design, improper installation, incomplete development, borehole instability and chemical, physical and/or biological incrustation. A brief description of the major factors leading to well maintenance are discussed below.

Design —

A well is improperly designed if hydrogeologic conditions, water quality or well intake design are not compatible with the purpose and use of the monitoring well. For example, if water is withdrawn during the sampling process and the well screen is plugged, the hydrostatic pressure on the outside of the casing may be great enough to cause collapse of the well intake if the strength of the material was not sufficient for the application. This is particularly true if the well intake material was chemically incompatible with the ground water and was weakened due to chemical reactions. Another example is where the operational life of the monitoring well exceeds the design life.

Table 41. Regional Well Maintenance Problems (Gass et al., 1980)

Ground Water Regions	Most Prevalent Aquifer Types	*Most Prevalent Well Problems
. Western Mountain Ranges	Alluvial	Silt, clay, sand intrusion, iron; scale deposition; biological fouling.
	Sandstone	Fissure plugging; casing failure; sand production.
	Limestone	Fissure plugging by clay and silt; mineralization of fissures.
2. Alluvial Basins	Alluvial	Clay, silt, sand intrusion; scale deposition; iron; biological fouling; limited recharge; casing failure.
3. Columbia Lava Plateau	Basaltic lavas	Fissure and vesicle plugging by clay and silt; some scale deposition.
	Alluvial	Clay, silt, sand intrusion; iron; manganese; biological fouling.
4. Colorado Plateau, Wyoming Basin	Interbedded sandstone and shale	Low initial yields; plugging of aquifer during construction by drilling muds and fines (clay and silt) natural to formations; fissure plugging; limited recharge; casing failure.
5. High Plains	Alluvial	Clay, silt, sand intrusion; scale deposition; iron; biological fouling; limited recharge.
	Interbedded sandstone, limestone, shale	Low initial yield; plugging of voids and fissures; poor development and construction; limited recharge.
6. Unglaciated Central Region	Alluvial	Clay, silt, sand intrusion; scale deposition; iron; biological fouling.
	Sandstone	Fissure plugging by clay and silt; casing failure; corrosion; salt water intrusion; sand production.
	Limestone	Fissure plugging by clay, silt, carbonate scale; salt water intrusion.
7. Glaciated Central Region	Alluvial	Clay, silt, sand intrusion; scale deposition; iron; biological fouling.
	Sandstone	Fissure plugging; sand intrusion; casing failure.
8. Unglaciated Appalachians	Metamorphic	Low initial yield; fissure plugging by silt and clay; mineraliztion of fissures.
	Limestone	Predominantly cavernous production; fissure plugging by clay and silt; mineralization of fissures.
	Alluvial	Clay, silt, fine sand intrusion; iron; scale; biological fouling.
9. Glaciated Appalachians	Alluvial	Clay, silt, sand intrusion; scale deposition; biological fouling; iron.
	Consolidated sedimentary	Fissure plugging; mineralization; low to medium initial yield.
0. Atlantic and Gulf Coast Plain	Alluvial and semiconsolidated	Clay, silt, sand intrusion; mineralization of screens; biological fouling.
	Consolidated sedimentary	Mechanical and chemical fissure plugging; biological fouling; incrustation of well intake structure.

* Excluding pumps and declining water table.

Table 42. Chemicals Used for Well Maintenance (Gass et al., 1980)

	Chemical Name	Formula	Application	Concentration
Acids and biocides	Hydrochloric acid	HCl	Carbonate scale, oxides, hydroxides	15%; 2-3 times zone volume
	Sulfamic acid	NH_2SO_3H	Carbonate scale, oxides, hydroxides	15%; 2-3 times zone volume
	Hydroxyacetic acid	$C_2H_4O_3$	Biocide, chelating agent, weak scale removal agent	
	Chlorine	Cl_2	Biocide, sterilization, very weak acid	50-500 ppm
Inhibitors	Diethyithiourea	$(C_2H_5)NCSN\ (C_2H_5)$	Metal protection	0.2%
	Dow A-73		Metal protection	0.01%
	Hydrated ferric sulfate	$Fe_2(SO_4)_3 \cdot 2\text{-}3H_2O$	For stainless steel	1%
	Aldec 97		With sulfamic acid	2%
	Polyrad 110A		Metal protection	.375%
Chelating agents	Citric acid	$C_6H_8O_7$	Keeps metal ions in solution	
	Phosphoric acid	H_3PO_4	Keeps metal ions in solution	
	Rochelle salt	$NaOOC\ (CHOH)_2\ COOK$	Keeps metal ions in solution	
	Hydroxyacetic acid	$C_2H_4O_3$	Keeps metal ions in solution	
Wetting agents	Plutonic F-68		Renders a surface non-repellent to a wetting liquid	
	Plutonic L-62		Renders a surface non-repellent to a wetting liquid	
Surfactants	Dow F-33		Lowers surface tension of water thereby increasing its cleaning power	
	Sodium Tripolyphosphate			
	Sodium Hexametaphosphate			

factors. The level of contamination and zone in which contamination occurs may modify the choice of technique. If no cross-contamination can occur between various zones and contamination cannot enter from the surface, grouting the well from bottom to top without removing the casing may be sufficient.

Well Abandonment Procedures

Well abandonment procedures involve filling the well with grout. The well may be filled completely or seals placed in appropriate zones and the well only partially filled with grout. Completely filling the well minimizes the possibility of borehole collapse and shifting of seals. The material used to fill the well can be either carefully selected natural material with a permeability that approximates the permeability of the natural formation or a grout mixture with a lower permeability. If more than one zone is present in the well, then either intermediate seals must be used with natural materials or the well must be grouted. Monitoring wells are most commonly abandoned by completely filling the well with a grout mixture.

Wells can be abandoned either by removing the casing or by leaving all or part of the casing in place and cutting the casing off below ground level. Because the primary purpose of well abandonment is to eliminate vertical fluid migration along the borehole, the preferred method of abandonment involves casing removal. If the casing is removed and the borehole is unstable, grout must be simultaneously emplaced as the casing is removed in order to prevent borehole collapse and an inadequate seal. When the casing is removed, the borehole can be sealed completely and there is less concern about channeling in the annular space or inadequate casing/grout seals. However, if the casing is left in place, the casing should be perforated and completely pressure-grouted to reduce the possibility of annular channeling. Perforating small-diameter casings in situ is difficult, if not impossible.

Many different materials can be used to fill the borehole. Bentonite, other clays, sand, gravel, concrete and neat cement all may have application in certain abandonment situations. Appendix C contains recommendations for well abandonment that are provided by the American Water Works Association (1984). These guidelines address the use of different materials for filling the borehole in different situations. Regardless of the type of material or combination of materials used for monitoring well abandonment, the sealant must be free of contaminants and must minimize chemical alteration of the natural ground-water quality. For example, neat cement should not be used in areas where the pH of the ground water is acidic. The ground water will attack the cement and reduce the effectiveness of the seal; the neat cement also raises the pH and alters ground-water chemistry.

Procedures for Removing Casing —

If the well was not originally grouted, the casing may be pulled by hydraulic jacks or by "bumping" the casing with a rig. A vibration hammer also may be used to speed up the task. Casing cutters can be used to separate the drive shoe from the bottom of the casing (Driscoll, 1986). If the well intake was installed by telescoping, the intake may be removed by sandlocking (United States Environmental Protection Agency, 1975).

A properly sized pulling pipe must, be used to successfully implement the sandlocking technique. Burlap strips, 2 to 4 inches wide, and approximately 3 feet long are tied to the pulling pipe. The pipe is lowered into the borehole to penetrate approximately 2/3 of the length of the well intake. The upper portion of the well intake above the burlap is slowly filled with clean angular sand by washing the sand into the well. The pulling pipe is then slowly lifted to create a locking effect. Constant pressure is applied and increased until the well intake begins to move. In some instances, jarring the pipe may assist in well intake removal, but in some cases this action may result in loss of the sand lock. As the well intake is extracted from the well, the sand packing and pipe are removed. Many contractors have developed variations of this sandlocking technique for specific situations. For example, slots can be cut in the pulling pipe at the level adjacent to the top of the well intake to allow excess sand to exit through the pulling pipe. These slots prevent the well intake from being overfilled and sandlocking the entire drill string. Slots can also be cut in the pipe just above the burlap so that sand can be backwashed or bailed from the inside pipe if the connection should need to be broken. Right and left-hand couplings located between the drill pipe and pulling pipe may be installed to disconnect the drill string if it becomes locked. Well intakes that are 2 to 6 inches in diameter can be removed by latch-type tools. For example, an elliptical plate cut in half with a hinge may be used. The plate folds as it is placed in the well and unfolds when lifted. If the well intake has a sump, the tool can be locked under the sump; if there is no sump, the tool can be locked under the well intake (Driscoll, 1986).

Another technique that may be used in conjunction with sandlocking involves filling the borehole with a clay-based drilling fluid through the pulling pipe while pulling the well intake and casing from the bottom. The fluid prevents the borehole from collapsing. The level of the fluid is observed to determine if the borehole is collapsing. Fluid rises if collapse is occurring. If fluid is falling, it is an indication that fluid is infiltrating into the surrounding formation. In this technique, the borehole is grouted from the bottom to the surface.

Overdrilling can also be used to remove casing from the borehole. In overdrilling, a large-diameter hollow-stem auger is used to drill around the casing. A large-diameter auger is used because a larger auger is less likely to veer off the casing during drilling. The hollow stem should be at least 2 inches larger than the casing that is being removed. For example, a 3 1/4-inch inside-diameter auger should not be used to overdrill a 2-inch diameter casing. The augers are used to drill to the full depth of the previous boring. If possible, the casing should be pulled in a "long" string, or in long increments. If the casing sticks or breaks, jetting should be used to force water down the casing and out the well intake. If this technique fails, the augers can be removed one section at a time and the casing can be cut off in the same incremental lengths. After all casing has been removed, the hollow-stem augers are reinserted and rotated to the bottom of the borehole. All the debris from the auger interior should be cleaned out, the augers extracted and the borehole filled with grout by using a tremie pipe (Wisconsin Department of Natural Resources, 1985). The technique of overdrilling is not limited to hollow-stem augers. Overdrilling can also be accomplished by direct rotary techniques using air, foam or mud.

calculated volume of the borehole and the volume of grout that was used; any discrepancy should be explained.

A concrete cap should be placed on the top of a cement/bentonite plug. The concrete cap should be marked with a piece of metal or iron pipe and then covered by soil. The metal allows for easy location of the well in the future by a metal detector or magnetometer.

Clean-up, Documentation and Notification

After abandonment is accomplished, proper site clean-up should be performed. For example, any pits should be backfilled and the area should be left clean (Fairchild and Canter, 1984). Proper and accurate documentation of all procedures and materials used should be recorded. If regulations require that abandonment of wells be reported, information should be provided on the required forms and in compliance with the state regulations. Table 43 shows information that is typically recorded on a well abandonment form. The location of abandoned wells should be plotted on a map and referenced to section lines, lot lines, nearby roads and buildings as well as any outstanding geological features (Aller, 1984).

Table 43. Well Abandonment Data (After Wisconsin Department of Natural Resources, 1985)

- Name of property owner
- Address of owner/property
- Well location (street, section number, township and range)
- Type of well installation method and date (drilled, driven, bored, dug), purpose of well (OW, PIEZ, LYS)
- Depth of well
- Diameter of well
- Depth of casing
- Depth to rock
- Depth to water
- Formation type
- Material overlying rock (clay, sand, gravel, etc.)
- Materials and quantities used to fill well in specific zones, detailing in which formations and method used
- Casing removed or left in place
- Firm completing work
- Signature of person doing work
- Address of firm

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Appendix A
Drilling and Constructing Monitoring Wells With Hollow-Stem Augers

[This report was produced as a part of this cooperative agreement and was published by Hackett (1987 and 1988).]

Introduction

Since the 1950's, hollow-stem augers have been used extensively by engineers and exploration drillers as a practical method of drilling a borehole for soil investigations and other geotechnical work. The widespread use and availability of hollow-stem augers for geotechnical investigations has resulted in the adaptation of this method to drilling and installing ground-water monitoring wells. To date, hollow-stem augers represent the most widely used drilling method among ground-water professionals involved in constructing monitoring wells (McCray, 1986). Riggs and Hatheway (1988) estimate that more than 90 percent of all monitoring wells installed in unconsolidated materials in North America are constructed by using hollow-stem augers.

The drilling procedures used when constructing monitoring wells with hollow-stem augers, however, are neither standardized nor thoroughly documented in the published literature. Lack of standardization is partially due to variable hydrogeologic conditions which significantly influence hollow-stem auger drilling techniques and monitoring well construction practices. Many of these construction practices evolved in response to site-specific drilling problems which are unique to hollow-stem augers.

This report presents an objective discussion of hollow-stem auger drilling and monitoring well construction practices. The drilling equipment will be reviewed, and the advantages and limitations of the method for drilling and installing monitoring wells will be presented.

Auger Equipment

The equipment used for hollow-stem auger drilling includes either a mechanically or hydraulically powered drill rig which simultaneously rotates and axially advances a hollow-stem auger column. Auger drills are typically mounted on a self-contained vehicle that permits rapid mobilization of the auger drill from borehole to borehole. Trucks are frequently used as the transport vehicle; however, auger drills may also be mounted on all-terrain vehicles, crawler tractors or tracked carriers (Mobile Drilling Company, 1983). These drilling rigs often have multi-purpose auger-core-rotary drills which have been designed for geotechnical work. Multi purpose rigs may have: 1) adequate power to rotate, advance and retract hollow-stem augers; 2) adequate drilling fluid pumping and tool hoisting capability for rotary drilling; and 3) adequate rotary velocity, spindle stability and spindle feed control for core drilling (Riggs, 1986).

The continuously open axial stem of the hollow-stem auger column enables the borehole to be drilled while the auger column simultaneously serves as a temporary casing to prevent possible collapse of the borehole wall. Figure 1 shows the typical components of a hollow-stem auger column. The lead end of the auger column is fitted with an auger head (i.e., cutter head) that contains replaceable teeth or blades which break up formation materials during drilling. The cuttings are carried upward by the flights which are welded onto the hollow stem. A pilot assembly, which is commonly comprised of a solid center plug and pilot bit (i.e., center head), is inserted within the hollow center of the auger head (Figure 1). The purpose of the center plug is to prevent formation materials from entering the

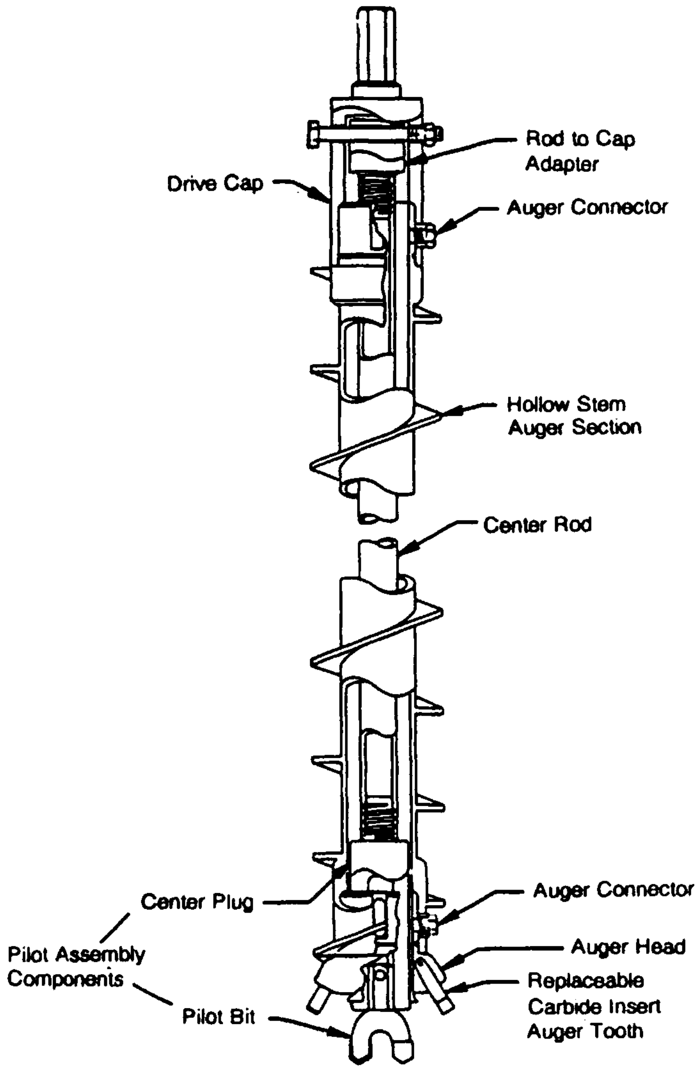

Figure 1. Typical components of a hollow-stem auger column (after Central Mine Equipment Company, 1987).

Table 1. Typical Hollow-Stem Auger Sizes with Slip-Fit, Box and Pin Connections (from Central Mine Equipment Company, 1987)

Hollow-Stem Inside Diameter (in.)	Flighting Diameter (in.)*	Auger Head Cutting Diameter (in.)
2 1/4	5 5/8	6 1/4
2 3/4	6 1/8	6 3/4
3 1/4	6 5/8	7 1/4
3 3/4	7 1/8	7 3/4
4 1/4	7 5/8	8 1/4
6 1/4	9 5/8	10 1/4
8 1/4	11 5/8	12 1/2

* NOTE: Auger flighting diameters should be considered minimum manufacturing dimensions.

Table 2. Hollow-Stem Auger Sizes with Threaded Connections (from Mobile Drilling Company, 1982)

Hollow-Stem Inside Diameter (in.)	Flighting Diameter (in.)*	Auger Head Cutting Diameter (in.)
2 1/2	6 1/4	8
3 3/8	8 1/4	9
4	8 1/2	11
6	11	13 1/4

* NOTE: Auger flighting diameters should be considered minimum manufacturing dimensions.

plers which are used with hollow-stem augers are split barrel and thin-walled tube samplers.

Split-barrel samplers are typically driven 18 to 24 inches beyond the auger head into the formation by a hammer drop system. The split-barrel sampler is used to collect a representative sample of the formation and to measure the resistance of the formation to penetration by the sampler. The samples are used for field indentification of formation characteristics and may also be used for laboratory testing. Thin-walled tube samplers may be advanced a variable length beyond the auger head either by pushing or driving the sampler into the formation. These samplers are designed to recover relatively undisturbed samples of the formation which are commonly used for laboratory testing. Standard practices for using split-barrel samplers and thin-wall tube samplers are established under ASTM Standards D1586-84 and D1587-83, respectively. The ability of hollow-stem augers to accommodate these samplers, and thus to permit the collection of undisturbed samples of the formation, is often cited as a major advantage of the hollow-stem auger method of drilling (Minning, 1982; Richter and Collectine, 1983; Gass, 1984).

In addition to these standard samplers, continuous sampling tube systems are commercially available which permit the collection of unconsolidated formation samples as the auger column is rotated and axially advanced (Mobile Drilling Company, 1983; Central Mine Equipment Company, 1987). Continuous sampling tube systems typically use a 5-foot barrel sampler which is inserted through the auger head. The barrel sampler replaces the traditional pilot assembly during drilling; however, the sampler does not rotate with the augers. The open end of the sampler extends a short but adjustable distance beyond the auger head, and this arrangement allows sampling to occur simultaneously with the advancement of the auger column. After the auger column has advanced a distance up to feet, the loaded sampler is retracted from the auger column. The loaded sampler is either immediately emptied and reinserted through the auger head or exchanged for another empty sampler. Multi-purpose drill rigs that are capable of core drilling can also use core barrels for coring either unconsolidated material or rock.

Borehole Drilling

There are several aspects of advancing a borehole with hollow-stem augers that are important considerations for ground-water monitoring. For clarity and continuity, the topic of drilling a borehole with hollow-stem augers will be presented under three subheadings: 1) general drilling considerations; 2) drilling with hollow-stem augers in the unsaturated and saturated zones; and 3) potential vertical movement of contaminants within the borehole.

General Drilling Considerations

When drilling with hollow-stem augers, the borehole is drilled by simultaneously rotating and axially advancing the auger column into unconsolidated materials or soft, poorly consolidated formations. The cutting teeth on the auger head break up the formation materials, and the rotating auger flights convey the cuttings upward to the surface. In unconsolidated materials, hollow-stem auger drilling can be relatively fast, and several hundred feet of borehole advancement per day is possible (Keely and Boateng, 1987a). Drilling may be much slower, however, in dense unconsoldiated materials and in coarse materials comprised primarily of cobbles. A major limitation of the drilling method is that the augers cannot be used to drill through consolidated rock. In unconsolidated deposits with boulders, the boulders may also cause refusal of the auger column. According to Keely and Boateng (1978a), this problem may be overcome in sediments with cobbles by removing the pilot assembly from the auger head and replacing the assembly with a small tri-cone bit. It is then possible to drill through the larger cobbles by limited rotary drilling, without the use of drilling fluids.

The depths to which a borehole may be advanced with a hollow-stem auger depend on the site hydrogeology (i.e., den-

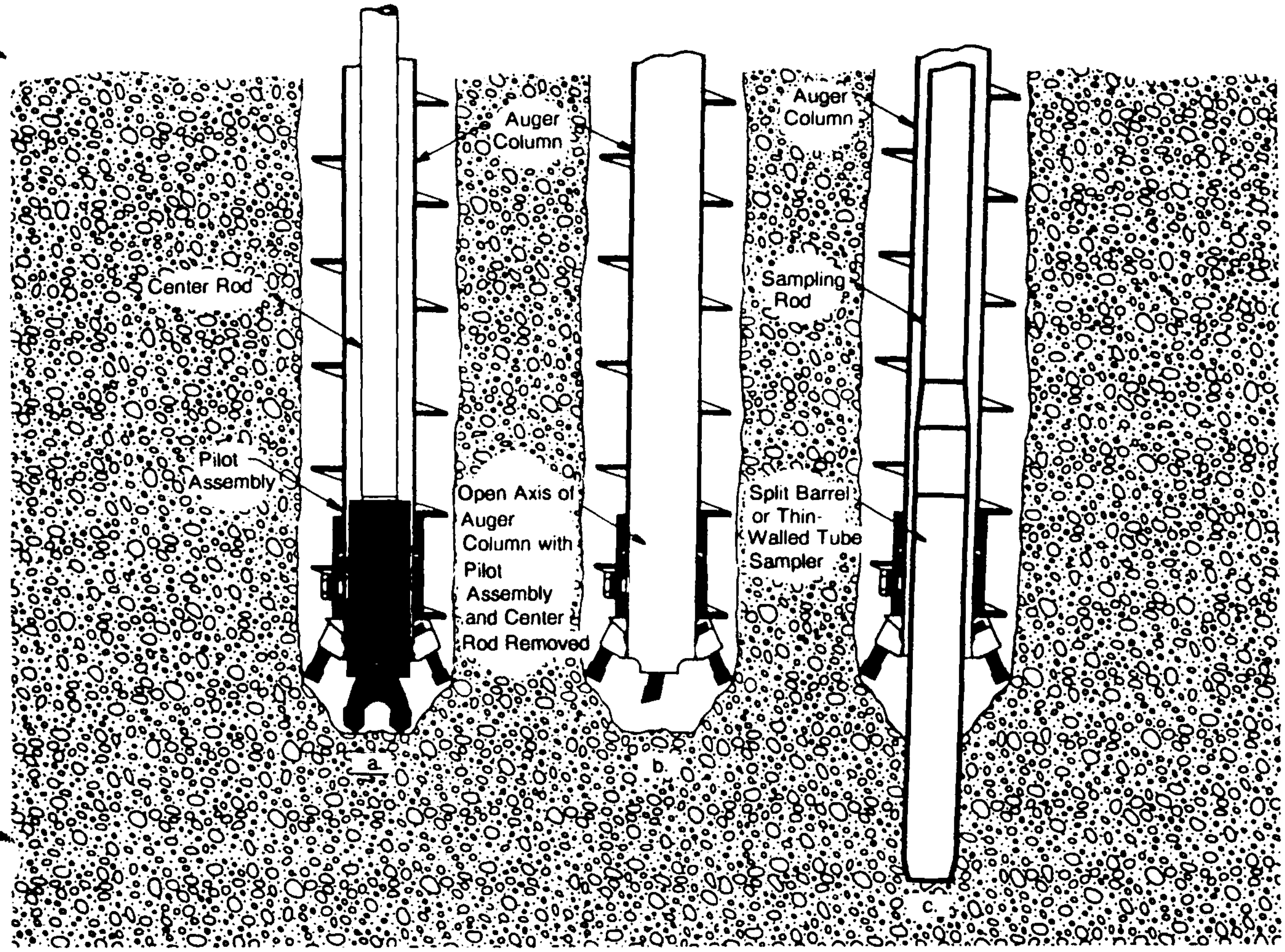

Figure 3. Sequential steps showing borehole advancement with pilot assembly and collection of a formation sample (after Riggs, 1983).

Heaving Sands —

The drilling techniques used to advance the auger column within heaving sands may vary greatly from those techniques used when drilling in unsaturated materials. The problem may occur when the borehole is advanced to a desired depth without the use of drilling fluids for the purpose of either sampling the formation or installing a monitoring well. As the pilot assembly is retracted, the hydrostatic pressure within the saturated sand forces water and loose sediments to rise inside the hollow center of the auger column (Figure 5). Keely and Boateng (1987a) report that these sediments can rise several tens of feet inside the lower auger sections. The resulting "plug" of sediment inside the hollow auger column can interfere with the collection of formation samples, the installation of the monitoring well or even additional drilling.

The difficulties with heaving sands may be overcome by maintaining a positive pressure head within the auger column. A positive pressure head can be created by adding a sufficient amount of clean water or other drilling fluid inside the hollow stem. Clean water (i.e., water which does not contain analytes of concern to a monitoring program) is usually preferred as the drilling fluid in order to minimize potential interference with samples collected from the completed well. The head of clean water inside the auger column must exceed the hydrostatic pressure within the sand formation to limit the rise of loose sediments inside the hollow-stem. Where the saturated sand formation is unconfined, the water level inside the auger column is maintained above the elevation of the water table. Where the saturated sand formation is confined, the water level inside the auger column is maintained above the potentiometric surface of the formation. If the potentiometric surface of the formation rises above the ground elevation, however, the heaving sand problem may be very difficult to counteract and may represent a limitation to the use of the drilling method.

There are several drilling techniques used to maintain a positive pressure head of clean water within the auger column. One technique involves injecting clean water through the auger column during drilling. This method usually entails removal of the pilot assembly, center rod and drive cap. A special coupling or adapter is used to connect the auger column to the spindle of

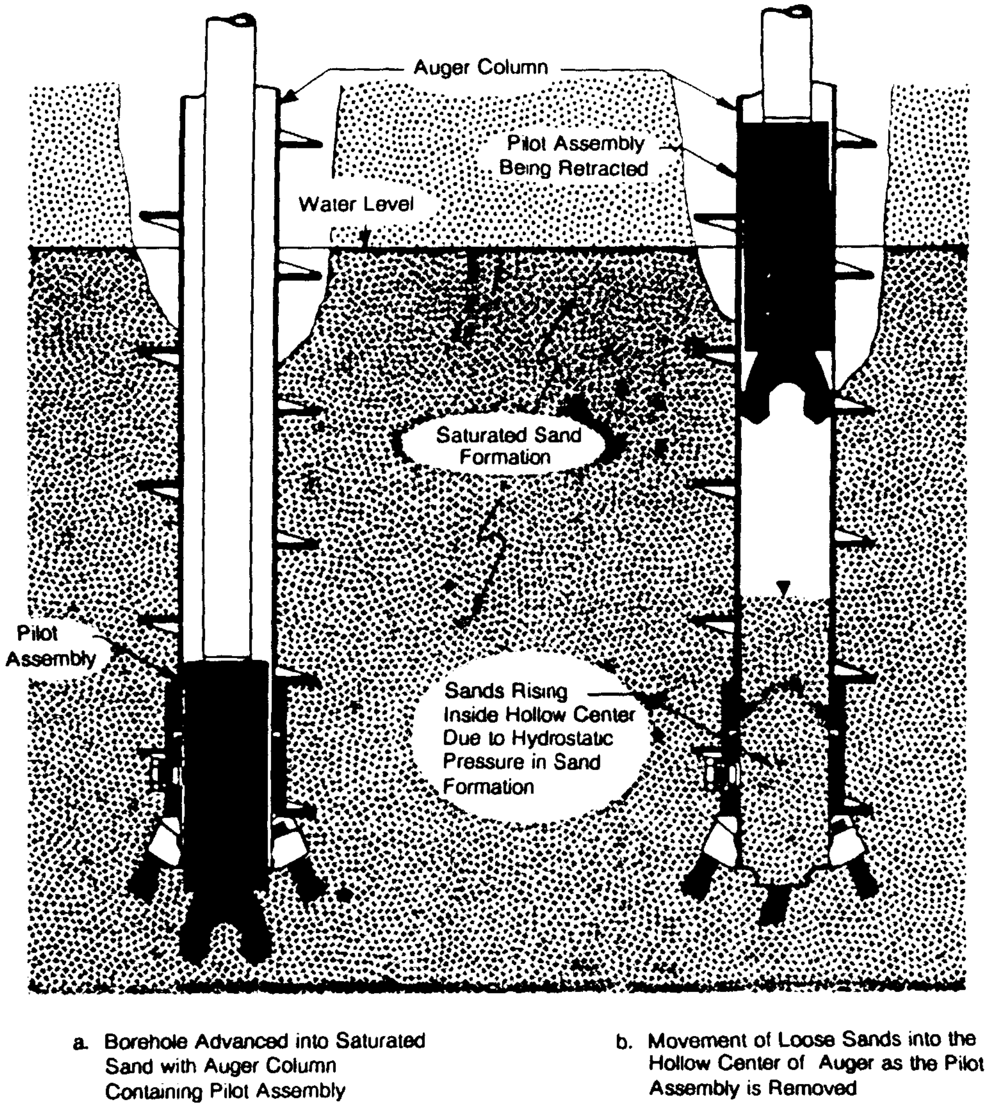

Figure 5. Diagram showing heaving sand with hollow-stem auger drilling.

traditional pilot assembly in the auger head. Some flexible center plugs are seated. inside the auger head by means of a specially manufactured groove in the hollow stem. These flexible center plugs allow split-barrel samplers and thin-walled tube samplers to pass through the center plug so that samples of the water bearing sands can be collected (Figure 13). The flexible center plug, however, cannot be retracted from the auger head and therefore severely restricts the ability to install a monitoring well through the auger column. The monitoring well intake and casing can be inserted through the flexible center plug, but the plug eliminates the installation of filter pack and annular sealant (i.e., bentonite pellets) by free fall through the working space between the well casing and auger column.

Potential Vertical Movement of Contaminants Within the Borehole

The potential for contaminants to move vertically within the borehole during drilling is an important consideration when ...cting a drilling method for ground-water monitoring. Ver-...al mixing of contaminants from different levels within a single borehole may be a problem with several different drilling methods, including hollow-stem augers. As the auger column advances through deposits which contain solid, liquid or gas-phase contaminants, there may be a potential for these contaminants to move either up or down within the borehole. Where vertical movement of contaminants occurs within the borehole, the cross contamination may be a significant source of sampling bias (Gillham et al., 1983).

Vertical movement of contaminants within the borehole may occur when contaminants from an overlying stratum are carried downward as residual material on the augers. The potential for small amounts of contaminated material to adhere to the auger head and lead auger is greatest in cohesive clayey deposits (Gillham et al., 1983). Contaminants may also adhere to split-barrel samplers and thin-walled tube samplers. If these sampling devices are not adequately cleaned between usage at successive sampling depths, contaminants from an overlying stratum may be introduced into a lower stratum via the sampling device. Where reaming techniques have enlarged the borehole beyond the outside diameter of the auger flights, contaminants

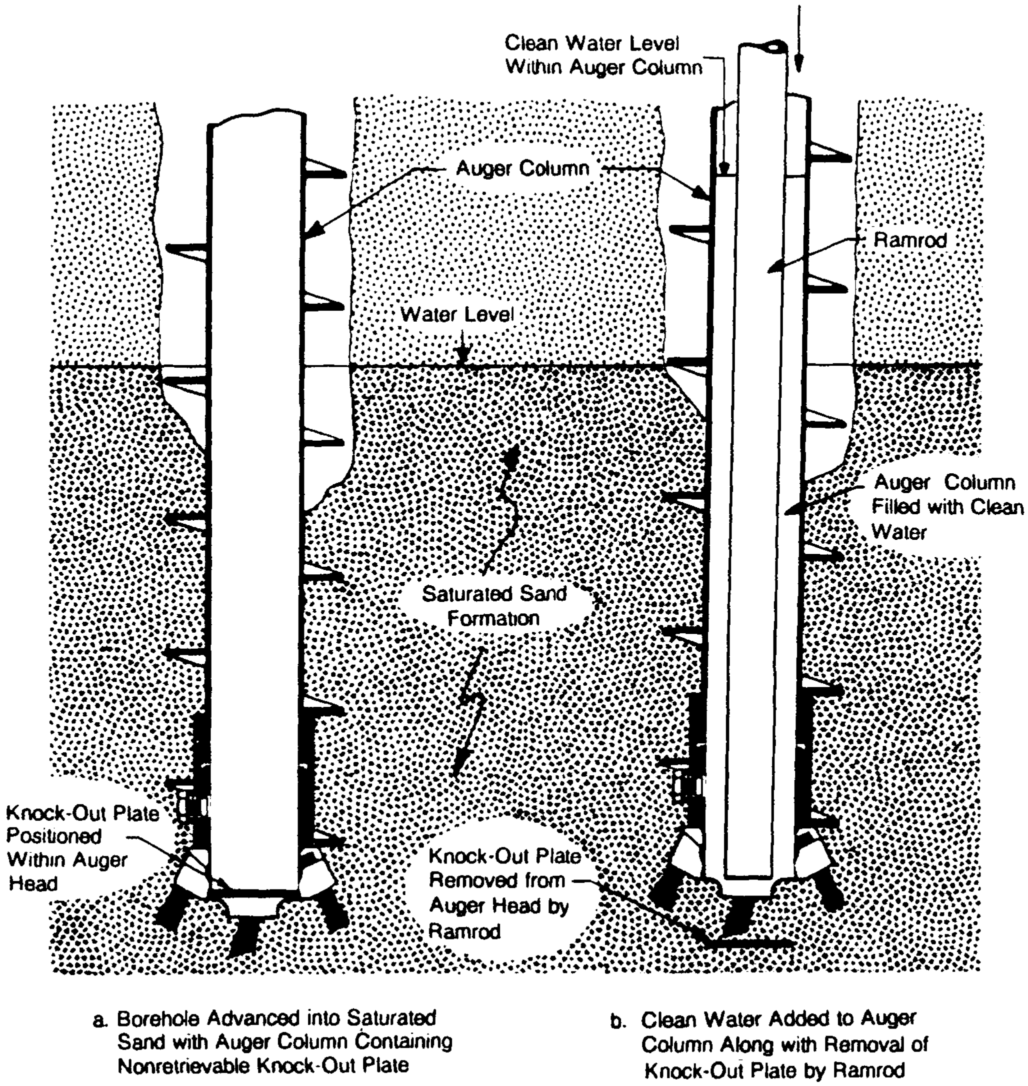

Figure 7. Use of a nonretrievable knock-out plate and auger column filled with clean water to avoid a heaving sand problem.

casing is then set and grouted into place. After grouting the large-diameter surface casing into place a hollow-stem auger column of smaller outside diamteter is used to advance the borehole to the desired depth for installation of the monitoring well (Figure 14c). Typical dimensions for augers used in this scenario might be an 8 1/4-inch diameter hollow-stem auger with an auger head cutting diameter of 12 1/2 inches to advance the borehole below the contaminated zone. A nominal 10-inch diameter surface casing would commonly be installed within the 12 1/2-inch diameter borehole. Four-and-one-quarter-inch diameter augers with an eight-and-one-quarter-inch auger head cutting diameter might then be used to continue drilling after the surface casing is set.

When the shallow geological formations are comprised of noncohesive materials and the borehole will not stand open, a hybrid drilling technique can be used in which the surface casing is advanced simultaneously with the auger column. According to Keely and Boateng (1987a), this alternate drilling technique is used to advance the auger column a few feet at a time and then to drive the surface casing to the new borehole depth. The auger column is telescoped inside the surface casing as the casing is driven outside the augers (Figure 15). Five-foot lengths of casing typically are used with this technique, and the casing is driven either by using the same conventional 140-pound drop hammer that is used to advance split-barrel samplers or a heavier 300-pound drop hammer. The sequential steps of augering and casing advancement continue until the surface casing extends below the depth of known contamination. Once the surface casing is set, a smaller diameter hollow-stem auger column can be used to advance the borehole to the desired depth for monitoring well installation.

Monitoring Well Installation

Monitoring wells may be constructed for water-quality sampling, water-level measurement or both. The intended purpose of the well influences the design components of a monitoring well. The following discussion will focus on techniques used to install water-quality monitoring wells which consist of a well casing and intake, filter pack and annular seal.

The methods used to construct water-quality monitoring wells with hollow-stem augers depend primarily on site hydrogeology. In particular, the cohesiveness of the formation

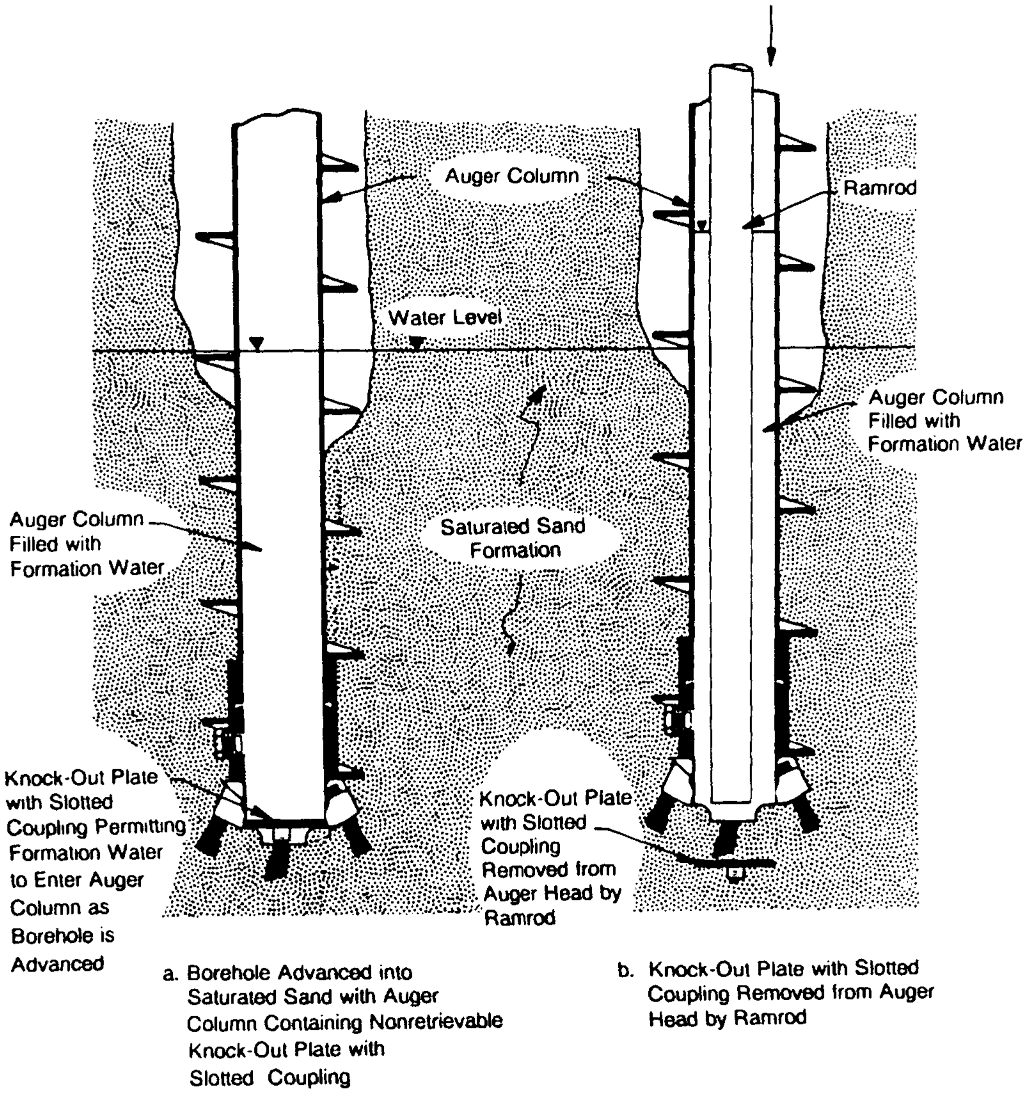

Figure 10. Use of a nonretrievable knock-out plate with a slotted coupling to avoid a heaving sand problem (after Perry and Hart, 1985).

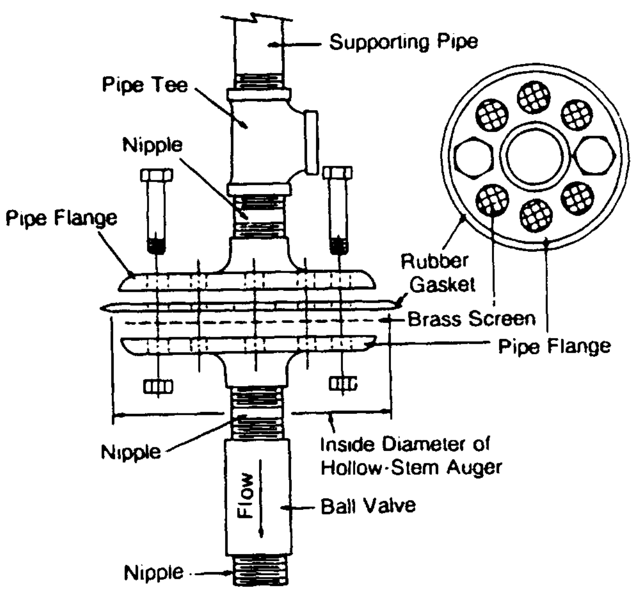

Figure 11. Diagram of a screened well swab (after Perry and Hart, 1985).

possible collapse of the borehole wall. When the auger column is used as a temporary casing during well construction, the hollow axis of the auger column facilitates the installation of the monitoring well casing and intake, filter pack and annular sealant. However, the practices that are used to emplace these well construction materials through the working space inside the hollow-stem augers are not standardized among contractors. Lack of standardization has resulted in concerns about the proper emplacement of the filter pack and annular seal in the monitoring well. To address these concerns, the topic of monitoring well construction through hollow-stem augers is presented in three separate discussions: 1) well casing diameter versus inside diameter of the hollow-stem auger; 2) installation of the filter pack; and 3) installation of the annular seal.

Well Casing Diameter Versus Inside Diameter of the Hollow-Stem Auger

Once the borehole has been advanced to the desired depth for installation of the monitoring well, the pilot assembly and center rod (if used) are removed, and the depth of the borehole is measured. A measuring rod or weighted measuring tape is lowered through the hollow axis of the auger column. This depth measurement is compared to the total length of the auger

Table 3. Maximum Working Space Available Between Various Diameters of Threaded, Flush-Joint Casing and Hollow-Stem Augers

Nominal Diameter of Casing (in.)	Outside Diameter of Casing *(in.)	Working Space "A" (see Figure 17) for Various Inside Diameter Hollow-Stem Augers ** (in.) 3 1/4	3 3/4	4 1/4	6 1/4	8 1/4
2	2.375	0.875	1.375	1.875	3.875	5.815
3	3.500	—	0.250	0.750	2.750	4.750
4	4.500	—	—	—	1.750	3.750
5	5.563	—	—	—	0.687	2.687
6	6.625	—	—	—	—	1.625

* Based on ASTM Standards D-1785 and F-480
** Inside diameters of hollow-stem augers taken from Table 1.

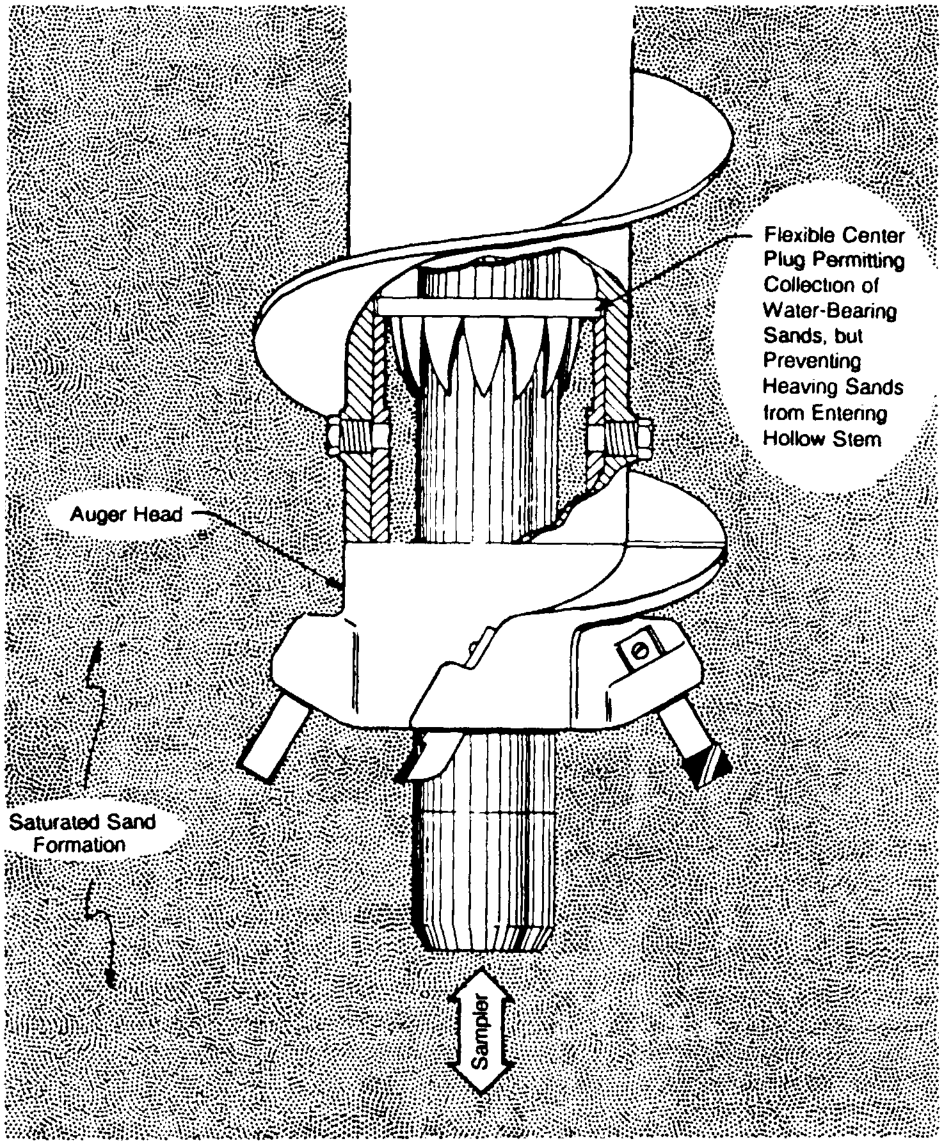

Figure 13. Flexible center plug in an auger head used to overcome heaving sands and permit sampling of formation materials (after Diedrich Drilling Equipment, 1986).

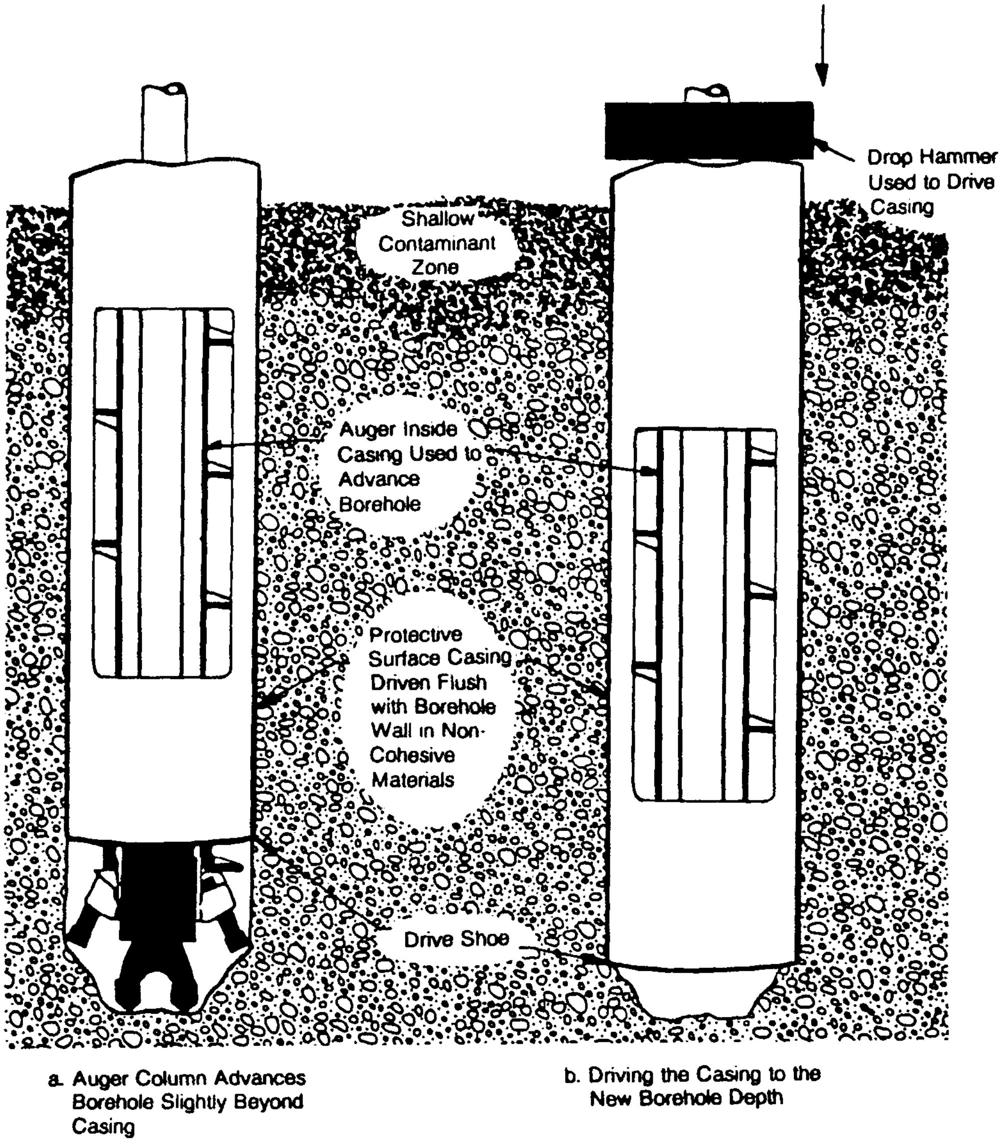

Figure 15. Sequence showing the installation of protective surface casing through a shallow contaminated zone in a noncohesive formation (after Keely and Boateng, 1987a).

monitoring well with a properly sized, graded and emplaced filter pack minimizes the extent to which the monitoring well will produce water samples with suspended sediments.

The filter pack typically extends from the bottom of the well intake to a point above the top of the intake (Figure 16). The filter pack is extended above the top of the well intake to allow for any settlement of the filter pack that may occur during well development and to provide an adequate distance between the well intake and the annular seal. As a general rule, the length of the filter pack is 10 percent greater than the length of the intake to compensate for settlement. United States Environmental Protection Agency (1986) recommends that the filter pack extend from the bottom of the well intake to a maximum height of 2 feet above the top of the intake, with the maximum height specified to ensure discrete sample horizons.

The thickness of the filter pack between the well intake and borehole wall generally will not be uniform because the well casing and intake usually are not centered in the hollow axis of the auger column. The filter pack, however, should be at least thick enough to completely surround the well intake. Tables 1 and 2 show that the cutting diameter of the auger head ranges from 4 to 7 1/4 inches larger than the inside diameter of the hollow-stem auger. When the well casing and intake are positioned toward one side of the inner hollow-stem wall (Figure 17), the annular space between the well intake and borehole wall may be as small as 2 to 3 5/8 inches. This annular space may still be adequate to preclude bridging and irregular emplacement of the filter pack; however, there is marginal tolerance for borehole sloughing or installation error. The proper installation of a filter pack with hollow-stem augers can be difficult if there is an inadequate working space between the casing and the auger column through which the filter pack is conveyed (Minning, 1982; Richter and Collentine, 1983; Gass, 1984; Schmidt, 1986; Keely and Boateng, 1987b).

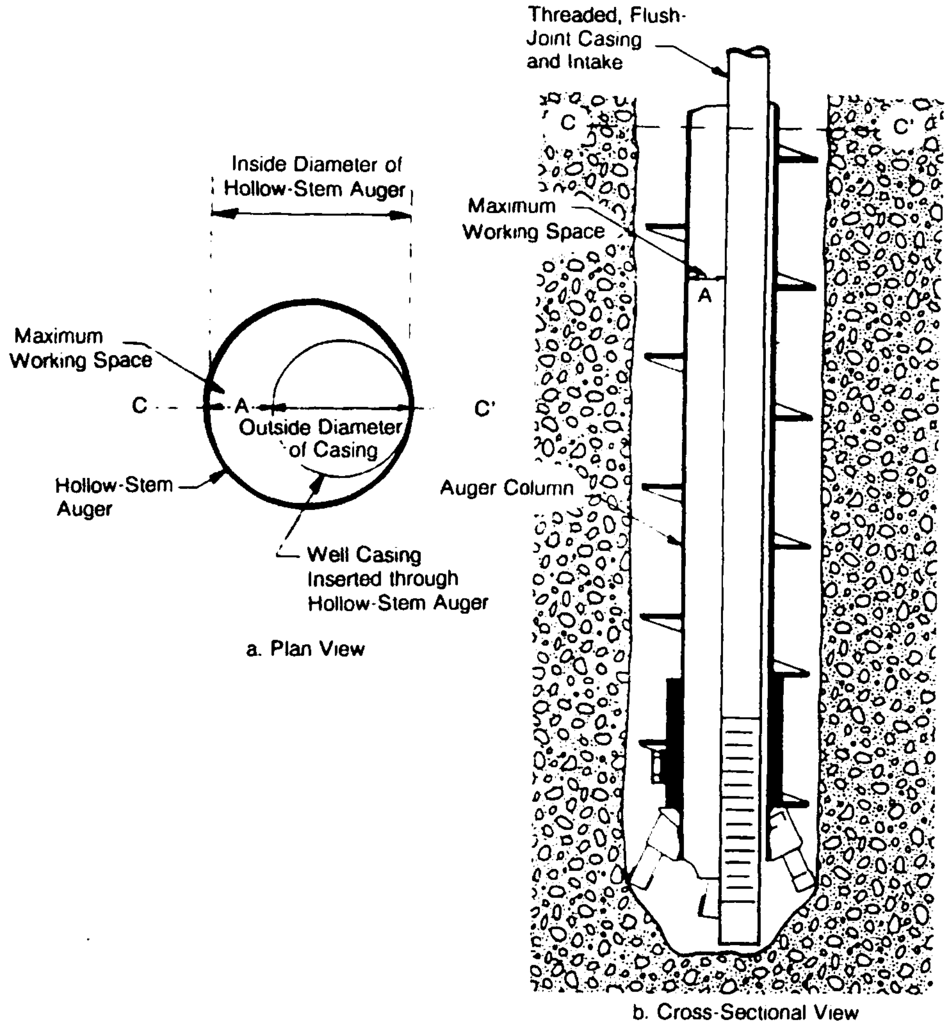

Figure 17. Plan and cross-sectional views showing the maximum working space (A) between the well casing and the hollow-stem auger.

pack in small amounts; and 3) carefully raising and lowering the measuring rod or weighted measuring tape while the filter pack is being added.

Segregation of graded filter pack material during free fall through the working space between the well casing and auger column may still occur, especially where the static water level between the casing and augers is shallow. As the sand-sized particles fall through the standing column of water, a greater drag is exerted on the smaller sand-sized particles due to the higher surface area-to-weight ratio. As a result, coarser particles fall more quickly through the column of water and reach the annular space between the well intake and borehole wall first. The coarser particles may therefore comprise the bottom portion of the filter pack, and the smaller-sized particles may comprise the upper portion of each segment of filter pack emplaced. Driscoll (1986) states that segregation may not be a significant problem when emplacing uniform grain size, well-sorted filter packs with a uniformity coefficient of 2.5 or less. However, graded filter packs are more susceptible to segregation problems, and this could result in the well consistently producing water samples with suspended sediment.

Potential bridging problems or segregation of graded filter packs may be minimized by using a tremie pipe to convey and emplace the filter pack. The use of a tremie pipe may be particularly important where the static water level between the well casing and auger column is shallow. Schmidt (1986) has suggested that at depths greater than 50 feet, a tremie pipe should be used to convey and emplace filter pack through hollow-stem augers. A tremie pipe is a hollow, thin-walled, rigid tube or pipe which is commonly fabricated by connecting individual lengths of threaded, flush-joint pipe. The tremie pipe should have a sufficient diameter to allow passage of the filter pack through the pipe. The inside diameter of a tremie pipe used for filter pack emplacement is typically 1 1/2 inches or greater to minimize potential bridging problems inside the tremie.

Emplacement of the filter pack begins by lowering a measuring rod or weighted measuring tape to the bottom of the borehole, as previously described in the free fall method of filter pack emplacement. The auger column commonly is retracted 1 to 2 feet, and the tremie pipe is lowered to the bottom of the borehole through the working space between the well casing and auger column (Figure 20a). A measured portion of the precalculated volume of filter pack is slowly poured down the tremie and the tremie is slowly raised as the filter pack discharges from the bottom of the pipe, filling the annular space between the well intake and borehole wall (Figure 20b). Once the filter pack is emplaced to the bottom of the auger

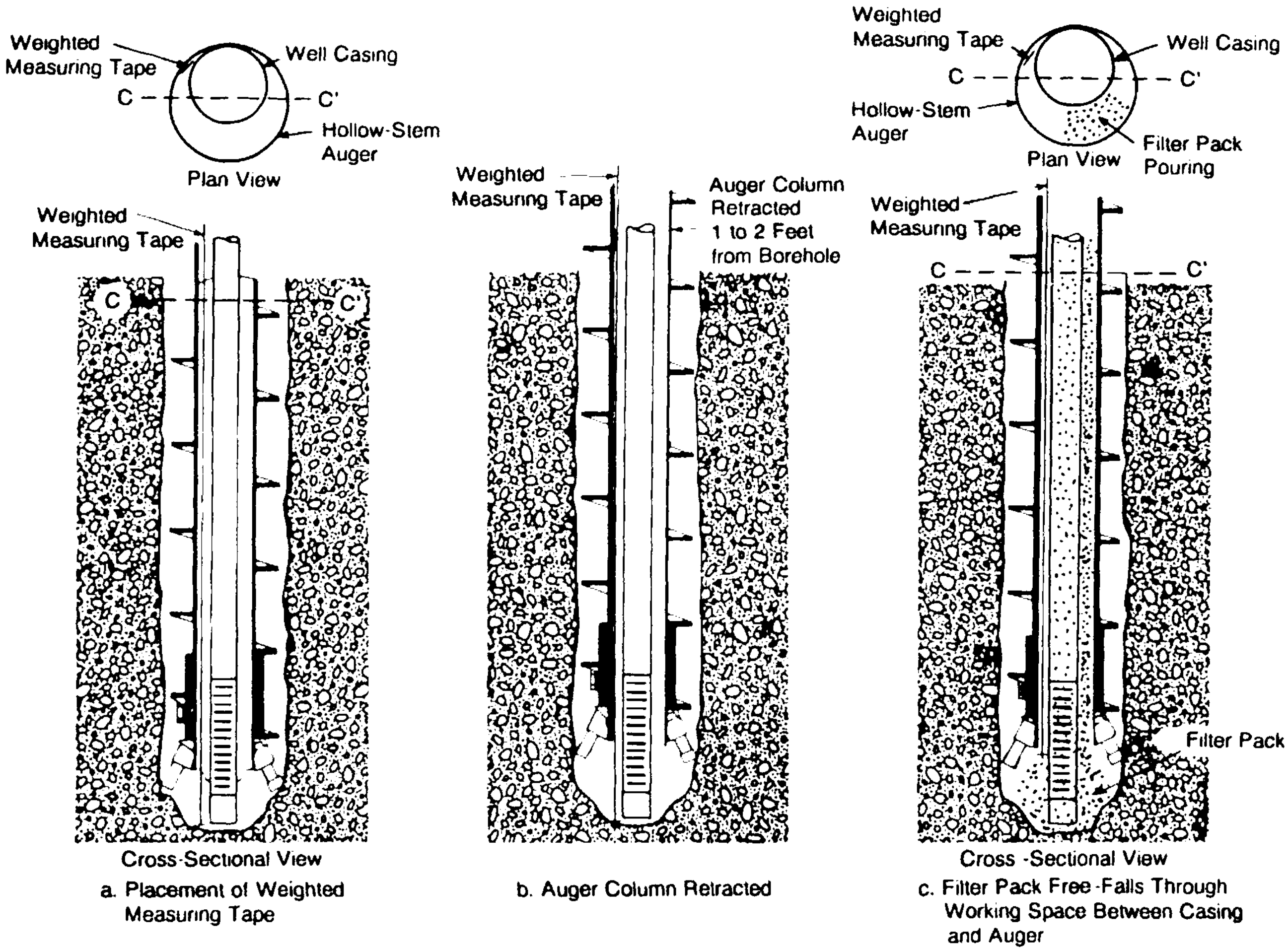

Figure 19. Free fall method of filter pack emplacement with a hollow-stem auger.

grained sediments extend to a desired height above the top of the well intake. The finer-grained fraction of the collapsed formation materials is later removed from the area adjacent to the well intake during well development.

Installation of the Annular Seal

Once the well intake, well casing and filter pack are installed through the hollow axis of the auger column, the final phase of monitoring well construction typically involves the installation of an annular seal. The annular seal is constructed by emplacing a stable, low permeability material in the annular space between the well casing and borehole wall (Figure 16). The sealant is commonly bentonite, expanding neat cement or a cement-bentonite mixture. The annular seal typically extends from the top of the filter pack to the bottom of the surface seal. The annular seal provides: 1) protection against the movement of surface water or near-surface contaminants down the casing-borehole annulus; 2) isolation of discrete sampling zones; and 3) prevention of the vertical movement of water in the casing-borehole annulus and the cross-contamination of strata. An effective annular seal requires that the casing-borehole annulus be completely filled with a sealant and that the physical integrity of the seal be maintained throughout the life of the monitoring well. The sealant should ideally be chemically nonreactive to minimize any potential impact the sealant may have on the quality of ground-water samples collected from the completed monitoring well.

Although bentonite and cement are the two most widely used annular sealants for monitoring wells, these materials have the potential for affecting the quality of ground-water samples. Bentonite has a high cation exchange capacity and may have an appreciable impact on the chemistry of the collected ground-water samples, particularly when the bentonite seal is in close proximity to the well intake (Gibb, 1987). Hydrated cement is highly alkaline and may cause persistent, elevated pH values in ground-water samples when the cement seal is near or adjacent to the well intake (Dunbar et al., 1985). Raising the pH of the ground water may further alter the solubility and presence of other constituents in the ground-water samples.

An adequate distance between the well intake and the annular sealant is typically provided when the filter pack is extended 2 feet above the top of the well intake. Bentonite pellets are commonly emplaced on top of the filter pack in the saturated zone (United States Environmental Protection Agency, 1986). Water in the saturated zone hydrates and expands the bentonite pellets thereby forming a seal in the casing-borehole annulus above the filter pack. The use of bentonite pellets directly on top of the filter pack generally is preferred because the pellet-form of bentonite may minimize auger column or to the outer surface of the well casing after having fallen only a few feet through a column of water between the casing and augers. Bentonite pellets may also stick together and bridge the working space between the casing and augers. As a result, the pellets may not reach the intended depth for proper annular seal emplacement. The bentonite pellets will continue to expand as the bentonite fully hydrates. An expanding bridge of bentonite pellets in the working space may eventually lock the well casing and auger column together causing the casing to pull back out of the borehole as the auger column is retracted.

Careful installation techniques can minimize the bridging of bentonite pellets in the working space between the casing and augers. These techniques include: 1) adequately sizing the working space between the well casing and auger column; 2) slowly adding individual bentonite pellets through the working space; and 3) frequently raising and lowering the measuring device to break up potential bridges of pellets. Driscoll (1986) reports that freezing the bentonite pellets or cooling the pellets with liquid nitrogen to form an icy outer coating may enable the bentonite pellets to free fall a greater depth through standing water before hydration of the pellets begins. The frozen bentonite pellets should, however, be added individually in the working space between the casing and augers to avoid clumping of the frozen pellets as they contact the standing water in the working space.

The potential problem of bentonite pellets bridging the working space between the well casing and auger column may be avoided by using instead a bentonite slurry, neat cement grout or cement-bentonite mixture pumped directly into the annular space between the well casing and borehole wall in the saturated zone. In the unsaturated zone, neat cement grout or a cement-bentonite mixture commonly is used as the annular sealant. In either instance, the slurry is pumped under positive pressure through a tremie pipe which is first lowered through the working space between the well casing and auger column. However, tremie emplacement of a bentonite slurry or cement-based grout directly on top of the filter pack is not recommended because these slurry mixtures may easily infiltrate into the filter pack. Ramsey et al., (1982) recommend that a 1 to 2-foot thick fine sand layer be placed on top of the filter pack prior to emplacement of the bentonite slurry or cement grout. The fine-sand layer minimizes the potential for the grout slurry to infiltrate into the filter pack. If bentonite pellets are initially emplaced on top of the filter pack, prior to the addition of a bentonite slurry or cement-based grout, the pellets serve the same purpose as the fine sand and minimize the potential for the infiltration of the grout slurry into the filter pack. When bentonite pellets are used, a suitable hydration period, as recommended by the manufacturer, should be allowed prior to the placement of the grout slurry. Failure to allow the bentonite pellets to fully hydrate and seal the annular space above the filter pack may result in the grout slurry infiltrating into the filter pack.

A side-discharge tremie pipe, rather than a bottom-discharge tremie pipe, should be used to emplace bentonite slurry or cement-based grouts above the filter pack. A side-discharge tremie may be fabricated by plugging the bottom end of the pipe and drilling 2 or 3 holes in the lower 1-foot section of the tremie. The pumped slurry will discharge laterally from the tremie and dissipate any fluid-pumping energy against the borehole wall and well casing. This eliminates discharging the pumped slurry directly downward toward the filter pack and minimizes the potential for the sealant to infiltrate into the filter pack.

Prior to emplacing a bentonite slurry or cement-based grout via the tremie method, the theoretical volume of slurry needed to fill the annular space between the well casing and borehole wall over the intended length of the annular seal is determined (see section on Installation of the Filter Pack for a discussion on how to calculate the theoretical volume of material needed). An additional volume of annular sealant should be prepared and readily available at the drill site to use if a discrepancy occurs between the volume of "annular sealant needed" versus "annular sealant used." The installation of the annular sealant should be completed in one continuous operation which permits the emplacement of the entire annular seal.

The procedure for emplacing a bentonite slurry or cement-based grout with a tremie pipe begins by lowering a measuring rod or weighted measuring tape through the working space between the well casing and auger column. A measurement of the depth to the top of the fine sand layer or bentonite pellet seal above the filter pack is taken and recorded. The auger column is commonly retracted 2 1/2 to 5 feet, and a side-discharge tremie pipe, with a minimum 1-inch inside diameter, is lowered through the working space between the casing and augers. The bottom of the tremie is positioned above the fine sand layer or bentonite pellet seal. A measured portion of the precalculated volume of bentonite slurry or cement-based grout is pumped through the tremie. The grout slurry discharges from the side of the pipe, filling the annular space between the well casing and borehole wall. As the grout slurry is pumped through the tremie, the measuring rod or weighted measuring tape is slowly raised and lowered to detect and measure the depth of slurry emplacement. Once the slurry is emplaced to the bottom of the auger column, the augers are retracted by using a winch line, the measuring rod or tape and tremie pipe may remain inside the working space between the casing and augers as the augers are pulled back from the borehole. Retracting the auger column with the winch line may also permit the option of pumping the grout slurry through the tremie while the auger column is simultaneously withdrawn from the borehole. A quick-disconnect fitting can be used to attach the grout hose to the top of the tremie pipe. This fitting allows the grout hose to be easily detached from the tremie as individual 5-foot auger sections are disconnected from the top of the auger column. By successively retracting the auger column and pumping the bentonite slurry or cement-based grout into the annular space between the well casing and borehole wall, the annular sealant is emplaced from the bottom of the annular space to the top. The tremie pipe can be moved upward as the slurry is emplaced, or it can be left in place at the bottom of the annulus until the annular seal is emplaced to the required height. Measurements of the depths of the emplaced annular seal are taken and recorded. Calculations of the theoretical volume of "annular sealant needed" versus "annular sealant used" should also be recorded, and any discrepancies should be explained.

Summary

Hollow-stem augers, like all drilling methods, have advantages and limitations for drilling and constructing monitor-

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Appendix B
Matrices for Selecting Appropriate Drilling Equipment

The most appropriate drilling technology for use at a specific site can only be determined by evaluating both the hydrogeologic setting and the objectives of the monitoring program. The matrices presented here were developed to assist the user in choosing an appropriate drilling technology. These matrices address the most prevalent hydrogeologic settings where monitoring wells are installed and encompass the drilling technologies most often applied. The matrices have been developed to act as guidelines; however, because they are subjective, the user is invited to make site-specific modifications. Prior to using these matrices, the prospective user should review the portion in Section 4 entitled "Selection of Drilling Methods for Monitoring Well Installation."

Several general assumptions were used during development of the matrices. These are detailed below:

1) Solid-flight auger and hollow-stem auger drilling techniques are limited to a practical drilling depth of 150 feet in most areas based on the equipment generally available;
2) Formation samples collected:
   a) during drilling with air rotary, air rotary with casing hammer and dual-wall air rotary techniques are assumed to be from surface discharge of the circulated sample;
   b) during drilling with solid-flight augers, hollow-stem augers, mud rotary or cable tool techniques are assumed to be taken by standard split-spoon (ASTM D1586) or thin-wall (ASTM D1587) sampling techniques to a depth of 150 feet at 5-foot intervals;
   c) below 150 feet, during mud rotary drilling are assumed to be circulated samples taken from the drilling mud at the surface discharge; and
   d) below 150 feet, during cable-tool drilling are assumed to be taken by bailer.

   If differing sampling methodologies are employed, the ratings for reliability of samples, cost and time need to be re-evaluated. (Wireline or piston sampling methods are available for use with several drilling techniques; however, these methods were not included in the development of the matrices);
3) Except for wells installed using driving and jetting techniques, the borehole is considered to be no less than 4 inches larger in diameter than the nominal diameter of the casing and screen used to complete the well (e.g., a minimum 6-inch borehole is necessary for completion of a 2-inch diameter cased well);
4) Artificial filter pack installation is assumed in all completions except for wells installed using driving and jetting techniques;
5) The development of ratings in the matrices is based on the largest expressed casing diameter in each range listed in the "General Hydrogeologic Conditions & Well Design Requirements" statement;
6) For purposes of the "General Hydrogeologic Conditions & Well Design Requirements," air is not considered as a drilling fluid; and
7) In the development of the dual-wall rotary technique ratings in the matrices, air is considered to be the circulation medium.

Each applicable drilling method that can be used in the described hydrogeologic setting and with the stated specific design requirements has been evaluated on a scale of 1 to 10 with respect to the criteria listed in the matrix. A total number for each drilling method was computed by adding the scores for the various criteria. The totals represent a relative indication of the desirability of drilling methods for the specified conditions.

MATRIX NUMBER 1

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid permitted; casing diameter 2 inches or less; total well depth 0 to 15 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	1	5	9	10	5	9	6	4	49
Driving	1	1	10	10	5	5	1	4	37
Jetting	2	1	8	10	5	1	1	1	29
Solid Flight Auger	3	4	7	9	10	4	5	2	44
Hollow Stem Auger	10	10	9	9	10	8	10	9	75
Mud Rotary	8	10	8	10	7	4	10	5	62
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	7	5	6	4	6	9	10	10	57
Dual Wall Rotary	7	8	6	1	6	9	10	9	56
Cable Tool	9	10	5	7	4	10	10	10	65

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. The shallow depth of up to 15 feet, and small completed well diameter of 2 inches or less allows maximum flexibility in equipment.

MATRIX NUMBER 3

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid permitted; casing diameter 2 inches or less; total well depth greater than 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	10	1	10	10	9	5	10	6	61
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	8	6	5	4	7	10	10	10	60
Dual Wall Rotary	10	10	8	1	10	10	10	10	69
Cable Tool	9	8	5	7	4	9	10	10	62

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Where dual-wall air techniques are used, completion is through the bit.
5. Depths greater than 150 feet limit technique choices.

MATRIX NUMBER 5

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid permitted; casing diameter 2 to 4 inches; total well depth 15 to 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	1	1	2	10	1	5	1	4	25
Jetting	1	1	3	10	3	1	1	1	21
Solid Flight Auger	3	3	2	9	7	4	2	2	32
Hollow Stem Auger	5	10	8	9	9	8	5	5	59
Mud Rotary	10	10	10	10	10	4	10	5	69
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	8	5	5	4	9	9	10	10	60
Dual Wall Rotary	10	8	8	1	8	10	8	8	61
Cable Tool	9	10	5	7	5	9	10	10	65

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Four-inch casing diameter limits technique choice even though depths are 15 to 150 feet. Large diameter (I.D.) hollow-stems are required. Solid flight augers require open-hole completion in potentially unstable materials.
5. With increasing depth, mud rotary, dual-wall rotary and cable tool techniques become favored.

MATRIX NUMBER 7

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid permitted; casing diameter 4 to 8 inches; total well depth 0 to 15 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	10	10	10	10	8	6	10	3	67
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	8	8	6	7	10	10	10	10	69
Dual Wall Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cable Tool	8	10	4	7	4	8	10	10	61

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Casing diameter 4 to 8 inches requires up to 12-inch borehole size and eliminates all techniques except mud rotary, cable tool and air rotary with casing hammer (that can usually drive large O.D. casing to shallow depth).

MATRIX NUMBER 9

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid permitted; casing diameter 4 to 8 inches; total well depth greater than 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	10	6	10	10	10	5	9	6	66
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dual Wall Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cable Tool	10	10	4	7	2	10	10	10	63

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Casing diameter 4 to 8 inches requires up to 12-inch borehole and eliminates all techniques except mud rotary and cable tool.

MATRIX NUMBER 11

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid not permitted; casing diameter 2 inches or less; total well depth 15 to 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	1	1	4	10	1	5	1	7	30
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	8	10	10	10	8	8	8	7	69
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	8	5	8	5	10	9	10	10	65
Dual Wall Rotary	10	8	8	1	8	9	10	10	64
Cable Tool	10	10	6	8	2	10	10	10	66

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction.
4. As depth increases the relative advantage of hollow-stem augering decreases.
5. Jetting and mud rotary methods would require the addition of fluid.
6. When using cable-tool drilling in saturated formations, it is assumed that no drilling fluid needs to be added in permeable materials and that small volumes of drilling fluid are permissible in less permeable materials.

MATRIX NUMBER 13

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid not permitted; casing diameter 2 to 4 inches; total well depth 0 to 15 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	1	1	10	10	5	1	1	4	33
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	1	1	7	10	5	1	1	2	28
Hollow Stem Auger	10	10	10	10	10	8	7	7	72
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	9	8	5	4	6	10	10	10	62
Dual Wall Rotary	9	8	5	1	5	10	8	8	54
Cable Tool	10	10	6	7	4	9	10	10	66

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction.
4. Increasing diameter is influencing choice of equipment.
5. Jetting and mud rotary methods would require the addition of fluid.
6. When using cable-tool drilling in saturated formations, it is assumed that no drilling fluid needs to be added in permeable materials and that small volumes of drilling fluid are permissible in less permeable materials.

MATRIX NUMBER 15

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid not permitted; casing diameter 2 to 4 inches; total well depth greater than 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	9	8	10	7	10	10	10	10	74
Dual Wall Rotary	10	10	9	4	10	10	9	8	70
Cable Tool	9	7	6	10	6	9	10	10	67

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction
4. Increasing diameter and depth favor cable tool and air rotary with casing hammer techniques.
5. Jetting and mud rotary methods would require the addition of fluid.
6. When using cable-tool drilling in saturated formations, it is assumed that no drilling fluid needs to be added in permeable materials and that small volumes of drilling fluid are permissible in less permeable materials.

MATRIX NUMBER 17

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; saturated; invasion of formation by drilling fluid not permitted; casing diameter 4 to 8 inches; total well depth 15 to 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dual Wall Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cable Tool	10	10	10	10	10	10	10	10	80

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly saturated, with saturation exerting significant influence on the choice of drilling technology.
2. Borehole stability problems are potentially severe.
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction.
4. Maximum diameter requiring 12-inch borehole exceeds practical equipment capability for depth range except for cable tool methods.
5. Jetting and mud rotary methods would require the addition of fluids.
6. When using cable-tool drilling in saturated formations, it is assumed that no drilling fluid needs to be added in permeable materials and that small volumes of drilling fluid are permissible in less permeable materials.

MATRIX NUMBER 19

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid permitted; casing diameter 2 inches or less; total well depth 0 to 15 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	4	5	9	10	5	9	6	6	54
Driving	7	1	10	10	6	5	1	4	44
Jetting	3	1	8	8	5	1	1	5	32
Solid Flight Auger	8	10	10	9	10	8	10	5	70
Hollow Stem Auger	10	10	10	9	10	10	10	10	79
Mud Rotary	8	10	7	10	8	4	10	5	62
Air Rotary	5	5	8	8	8	7	8	4	53
Air Rotary with Casing Hammer	9	8	6	4	3	9	10	10	59
Dual Wall Rotary	9	9	6	1	3	9	10	10	57
Cable Tool	6	10	3	7	2	9	10	7	54

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g., dense, silt/clay) to severe (e.g., coarse gravel and boulders).
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.

MATRIX NUMBER 21

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid permitted; casing diameter 2 inches or less; total well depth greater than 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	10	2	10	10	10	4	10	5	61
Air Rotary	5	5	8	8	7	8	10	4	55
Air Rotary with Casing Hammer	9	9	6	4	8	9	10	10	65
Dual Wall Rotary	10	10	6	1	8	10	10	9	64
Cable Tool	9	5	5	7	3	8	10	7	54

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g., dense, silt/clay) to servere (e.g., coarse gravel and boulders).
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Dual-wall air completion is through the bit.
5. Air rotary with casing hammer and dual-wall air methods become relatively more advantageous under these conditions.

MATRIX NUMBER 23

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid permitted; casing diameter 2 to 4 inches; total well depth 15 to 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	1	1	1	10	2	5	1	4	25
Jetting	1	1	1	10	3	1	1	1	19
Solid Flight Auger	3	10	10	9	8	8	6	5	59
Hollow Stem Auger	7	10	10	9	10	10	8	8	72
Mud Rotary	10	10	10	10	9	4	10	5	68
Air Rotary	5	5	8	8	8	7	6	4	51
Air Rotary with Casing Hammer	10	8	6	4	8	9	10	10	65
Dual Wall Rotary	10	9	6	1	8	9	10	9	62
Cable Tool	9	10	4	7	7	9	10	10	66

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g., dense, silt/clay) to servere (e.g., coarse gravel and boulders).
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Solid flight augers require open hole completion, which may or may not be feasible.

MATRIX NUMBER 25

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid permitted; casing diameter 4 to 8 inches; total well depth 0 to 15 feet.

DRILLING METHODS / CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	4	8	10	9	10	8	7	4	60
Hollow Stem Auger	7	10	10	9	9	8	7	4	64
Mud Rotary	10	10	7	10	8	5	10	3	63
Air Rotary	5	5	9	8	8	4	5	4	48
Air Rotary with Casing Hammer	8	7	6	4	8	10	10	10	63
Dual Wall Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cable Tool	8	10	3	7	4	10	10	9	61

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g., dense, silt/clay) to severe (e.g., coarse gravel and boulders).
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Diameter requirements limit the equipment that can be utilized.
5. Solid-flight augers require very difficult open-hole completion. Hollow-stem auger technique requires open-hole completion for casing sizes greater than 4 inches.

MATRIX NUMBER 27

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid permitted; casing diameter 4 to 8 inches; total well depth greater than 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	10	8	10	10	10	6	8	4	66
Air Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary with Casing Hammer	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dual Wall Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cable Tool	8	10	6	7	4	10	10	10	65

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g., dense, silt/clay) to servere (e.g., coarse gravel and boulders).
3. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
4. Diameter of borehole, and depth, eliminates most options.

MATRIX NUMBER 29

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid not permitted; casing diameter 2 inches or less; total well depth 15 to 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	1	1	7	10	6	5	1	4	35
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	9	10	10	10	9	8	9	5	70
Hollow Stem Auger	10	10	10	10	10	10	9	10	79
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	7	5	8	8	8	7	9	4	56
Air Rotary with Casing Hammer	10	8	6	4	6	9	10	10	63
Dual Wall Rotary	10	9	6	1	9	9	10	10	64
Cable Tool	NA	NA	NA	NA	NA	NA	NA	NA	NA

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g. dense, silt/clay) to severe (e.g. coarse gravel and boulders).
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction.
4. Jetting, mud rotary and cable tool methods would require the addition of fluid.
5. Air rotary with casing hammer requires driving 6-inch or greater diameter casing and completion by pullback.
6. Air rotary and solid-flight auger completion possible only if unsupported borehole is stable.

MATRIX NUMBER 31

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid not permitted; casing diameter 2 to 4 inches; total well depth 0 to 15 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	1	1	10	10	5	5	1	4	37
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	8	10	10	10	10	8	7	5	68
Hollow Stem Auger	10	10	10	10	10	10	9	8	77
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	5	5	8	8	8	7	8	4	53
Air Rotary with Casing Hammer	9	8	6	4	6	9	10	10	62
Dual Wall Rotary	9	9	6	1	6	9	9	10	59
Cable Tool	NA	NA	NA	NA	NA	NA	NA	NA	NA

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g. dense, silt/clay) to severe (e.g. coarse gravel and boulders).
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction.
4. Jetting, mud rotary and cable tool methods would require the addition of fluid.
5. Air rotary with casing hammer requires driving 8-inch or greater casing and completion by pullback.
6. Air rotary and solid-flight auger completion possible only if unsupported borehole is stable.

MATRIX NUMBER 33

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid not permitted; casing diameter 2 to 4 inches; total well depth greater than 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	5	5	10	10	10	5	10	5	60
Air Rotary with Casing Hammer	9	9	6	6	8	10	10	10	68
Dual Wall Rotary	10	10	6	4	10	10	10	10	70
Cable Tool	NA	NA	NA	NA	NA	NA	NA	NA	NA

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g. dense, silt/clay) to severe (e.g. coarse gravel and boulders).
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction.
4. No drilling fluid, increasing depth and diameter requirements eliminate many options.
5. Air rotary with casing hammer requires driving 8-inch or greater casing and completion by pullback.

MATRIX NUMBER 35

General Hydrogeologic Conditions & Well Design Requirements

Unconsolidated; unsaturated; invasion of formation by drilling fluid not permitted; casing diameter 4 to 8 inches; total well depth 15 to 150 feet.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	10	10	10	10	10	10	10	10	80
Air Rotary with Casing Hammer	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dual Wall Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cable Tool	NA	NA	NA	NA	NA	NA	NA	NA	NA

EXPLANATORY NOTES:

1. Unconsolidated formations, predominantly unsaturated, with monitoring conducted in individual, relatively isolated, saturated zones. Drilling is through primarily unsaturated material, but completion is in a saturated zone.
2. Borehole stability problems vary from slight (e.g. dense, silt/clay) to severe (e.g. coarse gravel and boulders).
3. The anticipated use of the monitoring well prohibits the use of drilling fluid and additives in construction.
4. No drilling fluid, depth and diameter requirements have eliminated options.
5. Oversize drillpipe and/or auxiliary air probably required.
6. Jetting, mud rotary and cable tool methods would require the addition of fluid.
7. Air rotary completion possible only if unsupported borehole is stable.
8. Air rotary with casing hammer unlikely to penetrate to specified depths with 12-inch diameter outer casing that is required for 8-inch diameter casing and screen completion.
9. If borehole is unstable, for 8-inch diameter casing there is no currently available method that can be used to fulfill the requirements as stated above. Therefore, fluid would be necessary to install the well and invasion-permitting matrices will apply.

MATRIX NUMBER 37

General Hydrogeologic Conditions & Well Design Requirements

Consolidated; invasion of formation by drilling fluid permitted; casing diameter 4 inches or less.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	7	6	8	10	8	7	10	7	63
Air Rotary	8	9	10	9	10	9	10	10	75
Air Rotary with Casing Hammer	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dual Wall Rotary	10	10	7	1	10	10	10	10	68
Cable Tool	8	7	5	6	4	7	10	8	55

EXPLANATORY NOTES:

1. Consolidated formations, all types
2. The anticipated use of the monitoring well permits the use of drilling fluid and additives in construction.
3. Boreholes are expected to be sufficiently stable to permit open-hole completion.
4. Core sampling will improve the relative value of the mud rotary method.
5. Where dual-wall air is available it becomes an equally preferred method with air rotary.

MATRIX NUMBER 39

General Hydrogeologic Conditions & Well Design Requirements

Consolidated; invasion of formation by drilling fluid not permitted; casing diameter 4 inches or less.

DRILLING METHODS \ CRITERIA FOR EVALUATION OF DRILLING METHODS	Versatility of Drilling Method	Sample Reliability	Relative Drilling Cost	Availability of Drilling Equipment	Relative Time Required for Well Installation and Development	Ability of Drilling Technology to Preserve Natural Conditions	Ability to Install Design Diameter of Well	Relative Ease of Well Completion and Development	TOTAL
Hand Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Driving	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jetting	NA	NA	NA	NA	NA	NA	NA	NA	NA
Solid Flight Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hollow Stem Auger	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mud Rotary	NA	NA	NA	NA	NA	NA	NA	NA	NA
Air Rotary	8	8	10	10	10	8	10	10	74
Air Rotary with Casing Hammer	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dual Wall Rotary	10	10	7	1	10	10	10	10	68
Cable Tool	NA	NA	NA	NA	NA	NA	NA	NA	NA

EXPLANATORY NOTES:

1. Consolidated formations, all types
2. The anticipated use of the monitoring well does not permit the use of drilling fluid and additives in construction.
3. Boreholes are expected to be sufficiently stable to permit open hole completion.
4. Both mud rotary and cable tool methods are potentially invasive, thereby reducing options to air drilling methods.
5. Air rotary may require extra air and/or special drill pipe.

Appendix C
(Supplement to Chapter 8)
Abandonment of Test Holes, Partially Completed Wells and Completed Wells
(American Water Works Association, 1984)

Section I.1 —General

The recommendations contained in this appendix pertain to wells and test holes in consolidated and unconsolidated formations. Each sealing job should be considered as an individual problem, and methods and materials should be determined only after carefully considering the objectives outlined in the standard.

Section I.2 — Wells in Unconsolidated Formations

Normally, abandoned wells extending only into consolidated formations near the surface and containing water under water-table conditions can be adequately sealed by filling with concrete, grout, neat cement, clay, or clay and sand. In the event that the water-bearing formation consists of coarse gravel and producing wells are located nearby, care must be taken to select sealing materials that will not affect the producing wells. Concrete may be used if the producing wells can be shut down for a sufficient time to allow the concrete to set. Clean, disinfected sand or gravel may also be used as fill material opposite the waterbearing formation. The remainder of the well, especially the upper portion, should be filled with clay, concrete, grout, or neat cement to exclude surface water. The latter method, using clay as the upper sealing material, is especially applicable to large diameter abandoned wells.

In gravel-packed, gravel-envelope, or other wells in which coarse material has been added around the inner casing to within 20 to 30 ft (6.1 to 9.1 m) of the surface, sealing outside the casing is very important. Sometimes this sealing may require removal of the gravel or perforation of the casing.

Section I.3 — Wells in Creviced Formations

Abandoned wells that penetrate limestone or other creviced or channelized rock formations lying immediately below the surface deposits should preferably be filled with concrete, grout, or neat cement to ensure permanence of the seal. The use of clay or sand in such wells is not desirable because fine-grained fill material may be displaced by the flow of water through crevices or channels. Alternate layers of coarse stone and concrete may be used for fill material through the water-producing horizon if limited vertical movement of water in the formation will not affect the quality or quantity of water in producing wells. Only concrete, neat cement, or grout should be used in this type of well. The portion of the well between a point 10 to 20 ft (3.0 to 6.1 m) below and a point 10 to 20 ft (3.0 to 6.1 m) above should be sealed and a plug of sealing material formed above the creviced formation. Clay or sand may be used to fill the upper part of the well to within 20ft (6.1 m) of ground level. The upper 20 ft (6.1 m) should be sealed with concrete or cement grout.

Section I.4 — Wells in Noncreviced Rock Formations

Abandoned wells encountering non-creviced sandstone or other water-bearing consolidated formations below the surface deposits may be satisfactorily sealed by filling the entire depth with clay, provided there is no movement of water in the well. Clean sand, disinfected if other producing wells are nearby, may also be used through the sandstone up to a point 10 to 20 ft (3.0 to 6.1 m) below the bottom of the casing. The upper portion of this type of well should be filled with concrete, neat cenent, grout or clay to provide an effective seal against entrance of surface water. If there is an appreciable amount of upward flow, pressure cementing or mudding may be advisable.

Section I.5 —Multiple Aquifer Wells

Some special problems may develop in sealing wells extending into more than one aquifer. These wells should be filled and sealed in such a way that exchange of water from one aquifer to another is prevented. If no appreciable movement of water is encountered, filling with concrete, neat cement, grout, or alternate layers of these materials and sand will prove satisfactory. When velocities are high, the procedures outlined in. Sec. I.6 are recommended. If alternate concrete plugs or bridges are used, they should be placed in known nonproducing horizons or, if locations of the nonproducing horizons are not known, at frequent intervals. Sometimes when the casing is not grouted or the formation is noncaving, it may be necessary to break, slit, or perforate the casing to fill any annular space on the outside.

Section I.6 — Wells with Artesian Flow

The sealing of abandoned wells that have a movement between aquifers or to the surface requires special attention. Frequently the movements of water may be sufficient to make sealing by gravity placement of concrete, cement grout, neat cement, clay or sand impractical. In, such wells, large stone aggregate (not more than one third of the diameter of the hole), lead wool, steel shavings, a well packer, or a wood or cast-lead plug or bridge will be needed to restrict the flow and thereby permit the gravity placement of sealing material above the formation producing the flow. If preshaped or precast plugs are used, they should be several times longer than the diameter of the well, to prevent tilting.

Since it is very important in wells of this type to prevent circulation between formations, or loss of water to the surfaces or to the annular space outside the casing, it is recommended that pressure cementing, using the minimum quantity of water that will permit handling, be used. The use of pressure mudding instead of this process is sometimes permissible.

Glossary

Abandonment

The complete sealing of a well or borehole with grout or other impermeable materials to restore the original hydrogeologic conditions and/or to prevent contamination of the aquifer.

Absorption

The penetration or apparent disappearance of molecules or ions of one or more substances into the interior of a solid or liquid. For example, in hydrated bentonite, the planar water that is held between the mica-like layers is the result of absorption (Ingersoll-Rand, 1985).

Accelerator

Substances used to hasten the setting or curing of cement such as calcium chloride, gypsum and aluminum powder.

Acrylonitrile Butadiene Styrene (ABS)

A thermoplastic material produced by varying ratios of three different monomers to produce well casing with good heat resistance and impact strength.

Adapter

A device used to connect two diferent sizes or types of threads, also known as sub, connector or coupling (Ingersoll-Rand, 1985).

Adsorption

The process by which atoms, ions or molecules are held to the surface of a material through ion-exchange processes.

Advection

The process by which solutes are transported with and at the same rate as moving ground water.

Air Rotary Drilling

A drilling technique whereby compressed air is circulated down the drill rods and up the open hole. The air simultaneously cools the bit and removes the cuttings from the borehole.

Air Rotary with Casing Driver

A drilling technique that uses conventional air rotary drilling while simultaneously driving casing. The casing driver is installed in the mast of a top-head drive air rotary drilling rig.

Aliphatic Hydrocarbons

A class of organic compounds characterized by straight or branched chain arrangement of the constituent carbon atoms joined by single covalent bonds with all other bonds to hydrogen atoms.

Alkalinity

The ability of the salts contained in the ground water to neutralize acids. Materials that exhibit a pH of 7 or greater are alkaline. High-pH materials used in well construction may have the potential to alter ambient water quality.

Aluminum Powder

An additive to cement that produces a stronger, quick-setting cement that expands upon curing.

Anisotropic

Having some physical property that varies with direction (Driscoll, 1986).

Annular Sealant

Material used to provide a positive seal between the borehole and the casing of the well. Annular sealants should be impermeable and resistant to chemical or physical deterioration.

Annular Space or Annulus

The space between the borehole wall and the well casing, or the space between a casing pipe and a liner pipe.

Aquifer

A geologic formation, group of formations, or part of a formation that can yield water to a well or spring.

Aquifer Test

A test involving the withdrawal of measured quantities of water from or addition of water to a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition (Driscoll, 1986).

Aquitard

A geologic formation, or group of formations, or part of a formation of low permeability that is typically 'saturated but yields very limited quantities of water to wells.

Aromatic Hydrocarbons

A class of unsaturated cyclic organic compounds containing one or more ring structures or cyclic groups with very stable bonds through the substitution of a hydrogen atom for an element or compound.

Artesian Well

A well deriving water from a confined aquifer in which the water level stands above the ground surface; synonymous with flowing artesian well (Driscoll, 1986).

Casing, Flush-Coupled

Flush-coupled casing is joined with a coupling with the same outside diameter as the casing, but with two female threads. The inside diameter of the coupling is approximately 3/16 inch smaller than that of the casing. Flush-coupled casing has thinner walls than flush-joint casing (Ingersoll-Rand, 1985).

Casing, Flush-Joint

Flush-joint casing has a male thread at one end and a female thread at the other. No coupling is used (Ingersoll-Rand, 1985).

Casing Driver

A device fitted to the top-head drive of a rotary rig that is used to advance casing into the subsurface.

Cation Exchange Capacity (CEC)

The measure of the availability of cations that can be displaced from sites on surfaces or layers and which can be exchanged for other cations. For geologic materials, CEC is expressed as the number of milliequivalents of cations that can be exchanged in a sample with a dry mass of 100 grams.

Cement

A mixture of calcium aluminates and silicates made by combining lime and clay while heating and which is emplaced in the annular space to form a seal between the casing and the borehole.

Cement Bond Log

A logging device that uses acoustical signals to determine the integrity of the cement bond to the casing.

Cement, Quick-Setting

Cement of special composition and fineness of grind that sets much quicker than ordinary cement. This cement is used for deviating holes and plugging cavities (Ingersoll-Rand, 1985).

Cementing

The emplacement of a cement slurry by various methods so that it fills the space between the casing and the borehole wall to a predetermined height above the bottom of the well. This secures the casing in place and excludes water and other fluids from the borehole.

Center Plug

A plug within the pilot assembly of a hollow-stem auger that is used to prevent formation materials from entering the stem of the lead auger during drilling.

Center Rod

A rod attached to the pilot assembly that facilitates removal from the lead end of the hollow-stem auger.

Centralizer

Spring-loaded guides that are used to center the casing in the borehole to ensure effective placement of filter pack or grout.

Check Valve

Ball and spring valves on core barrels, rods and bailers that are used to control water flow in one direction only.

Circulate

To cycle drilling fluid through the drill pipe and borehole while drilling operations are temporarily suspended to condition the drilling fluid and the borehole before hoisting the drill pipe and to obtain cuttings from the bottom of the well before drilling proceeds (Ingersoll-Rand, 1985).

Circulation

The movement of drilling fluid from the suction pit through the pump, drill pipe, bit and annular space in the borehole and back again to the suction pit. The time involved is usually referred to as circulation time (Ingersoll-Rand, 1985).

Circulation, Loss of

The loss of drilling fluid into the formation through crevices or by infiltration into a porous media.

Clay

A plastic, soft, variously colored earth, commonly a hydrous silicate of alumina, formed by the decomposition of feldspar and other aluminum silicates (Ingersoll-Rand, 1985).

Collapse Strength

The capability of a casing or well intake to resist collapse by any or all external loads to which it is subjected during and after installation.

Compressive Strength

The greatest compressive stress that a substance can bear without deformation.

Conductivity

A measure of the quantity of electricity transferred across unit area per unit potential gradient per unit time. It is the reciprocal of resistivity.

Cone of Depression

A depression in the ground-water table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of influence of a well (Driscoll, 1986).

Cone of Impression

A conical mound on the water table that develops in response to well injection whose shape is identical to the cone of depression formed during pumping of the aquifer.

Confined Aquifer

An aquifer which is bounded above and below by low-permeability formations.

Confined Bed

The relatively impermeable formation immediately overlying or underlying a confined aquifer.

Contaminant

Any physical, chemical, biological or radiological substance or matter in water that has an adverse impact.

Contamination

Contamination is the introduction into ground water of any contaminant migration (United States Environmental Protection Agency, 1986).

Down-the-Hole Hammer

A pneumatic drill operated at the bottom of the drill pipe by air pressure provided from the surface.

Drawdown

The extent of lowering of the water surface in a well and water-bearing zone resulting from the discharge of water from the well.

Drill Collar

A length of heavy, thick-walled pipe used to stabilize the lower drill string, to minimize bending caused by the weight of the drill pipe and to add weight to the bit.

Drill Pipe

Special pipe used to transmit rotation from the rotating mechanism to the bit. The pipe also transmits weight to the bit and conveys air or fluid which removes cuttings from the borehole and cools the bit (Driscoll, 1986).

Drill Rod

Hollow flush-jointed or coupled rods that are rotated in the borehole that are connected at the bottom to the drill bit and on the top to the rotating or driving mechanism of a drilling rig.

Drill String

The string of pipe that extends from the bit to the driving mechanism that serves to carry the mud down the borehole and to rotate the bit.

Drilling Fluid

A water or air-based fluid used in the well drilling operation to remove cuttings from the borehole, to clean and cool the bit, to reduce friction between the drill string and the sides of the borehole and to seal the borehole (Driscoll, 1986).

Drive Block

A heavy weight used to drive pipe or casing through unconsolidated material.

Drive Couplings

Heavy-duty couplings used to join sections of heavy-wall casing that are specifically designed to withstand the forces during driving casing.

Drive Head

A component fastened to the top of pipe or casing to take the blow of the drive block (Ingersoll-Rand, 1985).

Drive Shoe

A forged steel collar with a cutting edge fastened onto the bottom of the casing to shear off irregularities in the hole as the casing advances. It is designed to withstand drive pressures to protect the lower edge of the casing as it is driven (United States Environmental Protection Agency, 1986).

Driven Well

A well that is driven to the desired depth, either by hand or machine; may employ a wellpoint, or alternative equipment.

Drop Hammer

A weighted device used to drive samplers during drilling and sampling.

Dual-Wall Reverse Circulation

A drilling technique whereby the circulating fluid is pumped down between the outer casing and the inner drill pipe, through the drill bit and up the inside of the drill pipe.

Effective Grain Size (Effective Diameter)

The particle grain size of a sample where 90 percent represents coarser-size grains and 10 percent represents finer-size grains, i.e., the coarsest diameter in the finest 10 percent of the sediment.

Electric Logging

Logging techniques used in fluid-filled boreholes to obtain information concerning the porosity, permeability and fluid content of the formations drilled based on the dielectic properties of the aquifer materials.

Established Grade

The permanent point of contact of the ground or artificial surface with the casing or curbing of the well.

Established Ground Surface

The permanent elevation of the surface at the site of the well upon completion.

Filter Cake (Mudcake)

The suspended solids that are deposited on the borehole wall during the process of drilling.

Filter Cake Thickness (Mudcake)

A measurement, in 32nd of an inch, of the solids deposited on filter paper during the standard 30-minute API filter test, or measurement of the solids deposited on filter paper for a 7 1/2-minute duration (Ingersoll-Rand, 1985).

Filter Pack

Sand, gravel or glass beads that are uniform, clean and well-rounded that are placed in the annulus of the well between the borehole wall and the well intake to prevent formation material from entering through the well intake and to stabilize the adjacent formation.

Filter Pack Ratio

A ratio used to express size differential between the formation materials and the filter pack that typically refers to either the average grain size (D_{50}) or the 70-percent (D_{70}) retained size of the formation material.

Filtrate Invasion

The movement of drilling fluid into the adjacent formation that occurs when the weight of the drilling fluid substantially exceeds the natural hydrostatic pressure of the formation.

Fixed-Price Contracts

Drilling contracts that list the manpower, materials and additional costs needed to perform the work specified as a fixed cost payable upon completion.

Heaving Sand

Saturated sands encountered during drilling where the hydrostatic pressure of the formation is greater than the bore-hole pressure causing the sands to move up into the borehole.

High-Yield Drilling Clay

A classification given to a group of commercial drilling-clay preparations having a yield of 35 to 50 bbl/ton and intermediate between bentonite and low-yield clays. High-yield drilling clays are usually prepared by peptizing low-yield calcium montmorillonite clays or, in a few cases, by blending some bentonite with the peptized low-yield clay (Ingersoll-Rand, 1985).

Hollow-Stem Auger Drilling

A drilling technique in which hollow, interconnected flight augers, with a cutting head, are pressed downward as the auger is rotated.

Homogeneous

Exhibiting a uniform or similar nature.

Hydraulic Conductivity

A coefficient of proportionality that describes the rate at which a fluid can move through a permeable medium. It is a function of both the media and of the fluid flowing through it (United States Environmental Protection Agency, 1986).

Hydraulic Gradient

The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood be that of the maximum rate of decrease in head.

Hydrostatic Head

The pressure exerted by a column of fluid, usually expressed in pounds per square inch (psi). To determine the hydrostatic head at a given depth in psi, multiply the depth in feet by the density in pounds per gallon by 0.052 (Ingersoll-Rand, 1985).

Immiscible

Constituents that are not significantly soluble in water.

Incrustation (Encrustation)

The process by which a crust or coating is formed on the well intake and/or casing, typically through chemical or biological reactions.

Induction Tool

A geophysical logging tool used to measure pore fluid conductivity.

Inhibitor (Mud)

Substances generally regarded as drilling mud contaminants, such as salt and calcium sulfate, are called inhibitors when purposely added to mud so that the filtrate from the drilling fluid will prevent or retard the hydration of formation clays and shales (Ingersoll-Rand, 1985).

Isotropic

A medium whose properties are the same in all directions.

Jet Percussion

A drilling process that uses a wedge-shaped drill bit that discharges water under pressure while being raised and lowered to loosen or break up material in the borehole.

Kelly

Hollow steel bar that is in the main section of drill string to which power is directly transmitted from the rotary table to rotate the drill pipe and bit (Driscoll, 1986).

Ketones

Class of organic compounds where the carbonyl group is bonded to two alkyl groups (United States Environmental Protection Agency, 1986).

Knock-Out Plate

A nonretrievable plate wedged within the auger head that replaces the traditional pilot assembly and center rod that is used to prevent formation materials from entering the hollow auger stem.

Logging, Radioactive

The logging process whereby a neutron source is lowered down the borehole, followed by a recorder, to determine moisture content and to identify water-bearing zones.

Lost Circulation

The result of drilling fluid escaping from the borehole into the formation by way of crevices or porous media (Driscoll, 1986).

Louvered Intake

A well intake with openings that are manufactured in solid-wall metal tubing by stamping outward with a punch against dies that control the size of the openings.

Low-Solids Muds

A designation given to any type of mud where high-performing additives have been partially or wholly substituted for commercial or natural clays (Ingersoll-Rand, 1985).

Low-Yield Well

A relative term referring to a well that cannot recover in sufficient time after well evacuation to permit the immediate collection of water samples (United States Environmental Protection Agency, 1986).

Machine-Slotted Intake

Well intakes fabricated from standard casing where slots of a predetermined width are cut into the casing at regular intervals using machining tools.

Male and Female Threads

Now called pin and box threads, as in the oil industry (Ingersoll-Rand, 1985).

Marsh Funnel

A device used to measure drilling fluid viscosity where the time required for a known volume of drilling fluid to drain through an orifice is measured and calibrated against a time for

Perched Ground Water

Ground water in a saturated zone that is separated from the main body of ground water by a less permeable unsaturated zone or formation.

Percolate

The act of water seeping or filtering through materials without a definite channel.

Permeability

A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient (United States Environmental Protection Agency, 1975).

Piezometers

Generally a small-diameter, non-pumping well used to measure the elevation of the water table or potentiometric surface (United States Environmental Protection Agency, 1986).

Pilot Assembly

The assembly placed at the lead end of the auger consisting of a solid center plug and a pilot bit.

Plugs, Casing

Plug made of drillable material to correspond to the inside diameter of the casing. Plugs are pumped to bottom of casing to force all cement outside of casing (Ingersoll-Rand, 1985).

Plugging

The complete filling of a borehole or well with an impermeable material which prevents flow into and through the borehole or well.

Plume

An elongated and mobile column or band of a contaminant moving through the subsurface.

Polumeric Additives

The natural organic colloids developed from the guar plant that are used for viscosity control during drilling.

Polyvinyl Chloride (PVC)

Thermoplastics produced by combining PVC resin with various types of stabilizers, lubricants, pigments, fillers and processing aids, often formulated to produce rigid well casing.

Porosity

The percentage of void spaces or openings in a consolidated or unconsolidated material.

Portland Cement

Cement specified as Type I or Type II under ASTM C-150 standards.

Potentiometric Data

Ground-water surface elevations; obtained at wells and piezometers that penetrate a water-bearing formation.

Potentiometric Surface

An imaginary surface representing the total head of ground water in a confined aquifer that is defined by the level to which water will rise in a well (Driscoll, 1986).

Precipitate

Material that will separate out of solution or slurry as a solid under changing chemical and or physical conditions.

Pressure Sealing

A process by which a grout is confined within the borehole or casing by the use of retaining plugs or packers and by which sufficient pressure is applied to drive the grout slurry into and within the annular space or zone to be grouted.

Protective Casing

A string of casing set in the borehole to stabilize a section of the formation and/or to prevent leakage into and out of the formation and to allow drilling to continue to a greater depth.

Protectors, Thread

A steel box and pin used to plug each end of a drill pipe when it is pulled from the borehole to prevent foreign matter or abrasives from collecting on the greasy threads and to protect threads from corrosion or damage while transporting or in storage (Ingersoll-Rand, 1985).

Puddled Clay

Puddling clay is a mixture of bentonite, other expansive clays, fine-grained material and water, in a ratio of not less than 7 pounds of bentonite or expansive clay per gallon of water. It must be composed of not less than 50 percent expansive clay with the maximium size of the remaining portion not exceeding that of coarse sand.

Pulling Casing

To remove the casing from a well.

Pumping/Overpumping/Backwashing

A well development technique that alternately starts and stops a pump to raise and drop the column of water in the borehole in a surging action.

Pump Test

A test used to determine aquifer characteristics performed by pumping a well for a period of time and observing the change in hydraulic head that occurs in adjacent wells. A pump test may be used to determine degree of hydraulic interconnection between different water-bearing units, as well as the recharge rate of a well (United States Environmental Protection Agency, 1986).

Pumping Water Level

The elevation of the surface of the water in a well or the water pressure at the top of a flowing artesian well after a period of pumping or flow at a specified rate.

Radioactive Logging

A logging process whereby a radioactive source is lowered down a borehole to determine formation characteristics. Radioactive logging devices typically used for ground-water investigations include gamma and neutron logging probes.

Radius of Influence (Cone of Depression)

The radial distance from the center of a well under pumping water into or from a well, and the subsequent measurement of the resulting well recovery (United States Environmental Protection Agency, 1986).

,lurry

A thin mixture of liquid, especially water, and any of several finely divided substances such as cement or clay particles (Driscoll, 1986).

Smectite

A commonly used name for clay minerals that exhibit high swelling properties and a high cation exchange capacity.

Sodium Bentonite

A type of clay added to drilling fluids to increase viscosity.

Solids Concentration or Content

The total amount of solids in a drilling fluid as determined by distillation that includes both the dissolved and the suspended or undissolved solids. The suspended solids content may be a combination of high and low specific gravity solids and native or commercial solids. Examples of dissolved solids are the soluble salts of sodium, calcium and magnesium. Suspended solids make up the mudcake; dissolved solids remain in the filtrate. The total suspended and dissolved solids contents are commonly expressed as percent by weight (Ingersoll-Rand, 1985).

Solid-Flight Auger

A solid-stem auger with a cutting head and continuous flighting that is rotated by a rotary drive head at the surface and rced downward by a hydraulic pulldown or feed device.

Solvation

The degradation of plastic well casing in the presence of very high concentrations of specific organic solvents.

Solvent Cementing

A method of joining two sections of casing where solvent is applied to penetrate and soften the casing pieces and fuses the casing together as the solvent cement cures.

Sorption

The combined effect of adsorption and/or absorption.

Specific Capacity

The rate of discharge of water from a well per unit of drawdown of the water level, commonly expressed in gpm/ft or m^3 /day/m, and that varies with the duration of discharge (Driscoll, 1986).

Specific Yield

The ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity to the volume of the mass expressed as a percentage (Driscoll, 1986).

Split-Spoon Sampler

A hollow, tubular sampling device driven by a 140-pound :ight below the drill stem to retrieve sample of the formation.

Spudding Beam

See Walking Beam.

Standard Dimension Ratio

A ratio expressed as the outside diameter of casing divided by the wall thickness.

Static Water Level

The distance measured from the established ground surface to the water surface in a well neither being pumped nor under the influence of pumping nor flowing under artesian pressure.

Surface Seal

The seal at the surface of the ground that prevents the intrusion of surficial contaminants into the well or borehole.

Surfactant

A substance capable of reducing the surface tension of a liquid in which it is dissolved. Used in air-based drilling fluids to produce foam, and during well development to disaggregate clays (Driscoll, 1986).

Surge Block

A plunger-like tool consisting of leather or rubber discs sandwiched between steel or wooden discs that may be solid or valved that is used in well development.

Surging

A well development technique where the surge block is alternately lifted and dropped within the borehole above or adjacent to the screen to create a strong inward and outward movement of water through the well intake.

Swivel, Water

A hose coupling that forms a connection between the slush pumps and the drill string and permits rotation of the drill string (Ingersoll-Rand, 1985).

Teflon

Trade name for fluoropolymer material.

Telescoping

A method of fitting or placing one casing inside another or of introducing screen through a casing diameter larger than the diameter of the screen (United States Environmental Protection Agency, 1975).

Temperature Survey

An operation to determine temperatures at various depths in the wellbore, typically used to ensure the proper cementing of the casing or to find the location of inflow of water into the borehole (Ingersoll-Rand, 1985).

Tensile Strength

The greatest longitudinal stress a substance can bear without pulling the material apart.

Test Hole

A hole designed to obtain information on ground-water quality and/or geological and hydrological conditions (United States Environmental Protection Agency, 1975).

pumping equipment or aquifer tests. May also refer to casing and intake.

Well Cap

An approved, removable apparatus or device used to cover a well.

Well Cluster

Two or more wells completed (screened) to different depths in a single borehole or in a series of boreholes in close proximity to each other. From these wells, water samples that are representative of different horizons within one or more aquifers can be collected (United States Environmental Protection Agency, 1986).

Well Construction

Water well construction means all acts necessary to obtain ground water from wells.

Well Contractor

Any person, firm or corporation engaged in the business of constructing, altering, testing, developing or repairing a well or borehole.

Well Development

Techniques used to repair damage to the borehole from the drilling process so that natural hydraulic conditions are restored; yields are enhanced and fine materials are removed.

Well Evacuation

Process of removing stagnant water from a well prior to sampling (United States Environmental Protection Agency, 1986).

Well Intake (Well Screen)

A screening device used to keep materials other than water from entering the well and to stabilize the surrounding formation.

Well Log

A record that includes information on well construction details, descriptions of geologic formations and well testing or development techniques used in well construction.

Well Point

A sturdy, reinforced well screen or intake that can be installed by driving into the ground.

Well Seal

An arrangement or device used to cover a well or to establish or maintain a junction between the casing or curbing of a well and the piping or equipment installed therein to prevent contaminated water or other material from entering the well at the land surface.

Well Vent

An outlet at or near the upper end of the well casing to allow equalization of air pressure in the well.

Yield

The quantity of water per unit of time that may flow or be pumped from a well under specified conditions.

Yield Point

A measure of the amount of pressure, after the shutdown of drilling fluid circulation, that must be exerted by the pump upon restarting of the drilling fluid circulation to start flow.

Zone of Aeration

The zone above the water table and capillary fringe in which the interstices are partly filled with air.

Zone of Saturation

The zone below the water table in which all of the interstices are filled with ground water.

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☆ U.S. GOVERNMENT PRINTING OFFICE:1991-548-187/20595

Association of Engineering Geologists
1992-Annual Meeting
Hosted by the AEG
Southern California Section

Groundwater Monitoring and Remediation Techniques Short Course

Monday - October 5, 1992 - 8 Hours Duration

Sheraton Long Beach Hotel, 333 E. Ocean Boulevard, Long Beach, California

Instructors

Kelly E. Rowe, C.E.G.
Victor E. Harris, C.E.G.
Donn Marrin, Ph.D.
Robert Evangelista

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Groundwater Monitoring and Remediation Techniques

at the

Annual Association's Meeting
in Long Beach, California
October 5th, 1992

Kelly E. Rowe
Chairman, AEG
Southern California Section

Treatment Parameters

- Flow Rate
- Chemicals of Concern
- Influent Concentration
- Discharge Requirements

Flow Rate

- Flow Rate is a Design Variable

- Must Evaluate the Effect of Flow Rate on the Total Cost of the System and on the Time that is Needed for Clean-Up

Flow Rate Factors

First:

- Is the Flow Rate Necessary to Stop and Reverse the Movement of the Contamination Plume?
- Is it Desirable or CostEffective to Use Groundwater Control and Containment Methods, Such as Slurry Wall, to Stop the Movement of a Plume?

Flow Rate Factors

Second: What is the Amount of Groundwater Entering the Site?

- Groundwater for Up Gradient
- Surface Water from Rain and Run-off
- Confining Layer Below Aquifer Can Have Cracks and Fissures

May Be Able to Cap Surface with Impermeable Layer or Provide Good Drainage Away From Site to Reduce Surface Water

Flow Rate Factors

Third: Speed of the Clean-Up

- A Complicated Relationship Between Pumping Rate, System Design, and Remediation Time

- Must Decide Between the Cost of Increasing the Treatment System Size and the Cost Savings of Decreasing Clean-Up Time

Flow Rate Factors

Speed of the Clean-Up

What is the Relationship Between System Flow and Clean-Up Time?

- Necessary to Identify the Source or Sources of Contamination

- Next, Stop the Source(s) for Contributing to the Plume. May Need to Slow Clean-Up to Use Flushing Methods to Mobilize Contaminants into the Plume

- Seasonal Variation in Groundwater Levels May Occur. Contamination Remaining in the Unsaturated Zone During the Low Water Season May Require Slow Treatment Rate Over Several High Water Season.

Other Flow Rate Factors

The number of recovery wells or trenches used and their effectiveness at recovering the plume and remediating the site

A recovery system located closer to the leading edge of the plume will require less water (flow) to capture the contaminants but clean water will also be recovered

More flow will be required if some of the water is to be used to flush the unsaturated zone of contaminants. Although this technique may reduce the overall remediation time, increasing the total water to the site will increase the flow to the treatment system

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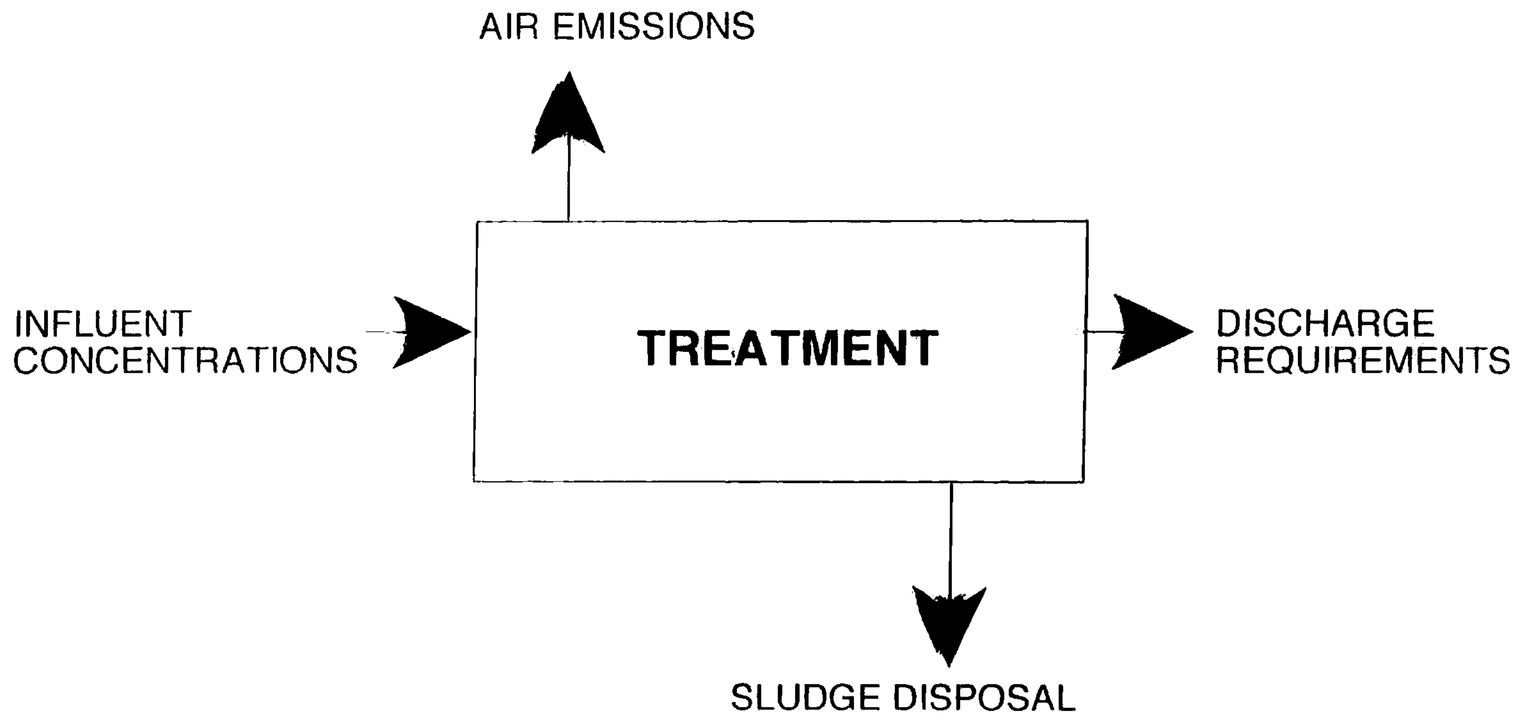
Parameters For Defining A Treatment System



Influent Concentration

Major factors affecting the concentration of contaminants

- The distance of the well from the original entrance of the contaminants to the aquifer
- The amount of material reaching the aquifer
- The solubility of the contaminants in water
- The relative density compared to water
- The biological and chemical transformation of the contaminants

Influent Concentration

Minor factors affecting the concentration of contaminants

- Rate of groundwater flow
- Mixing characteristics in the aquifer
- The combined effect of the above factors on concentration

Discharge Requirements

System design depends on the final disposition of the treated groundwater

- *Surface Water Body.* Regulated by the National Pollution Discharge Elimination System (NPDES) program. Determine if the discharge is direct or indirect, a regulated categorical discharge, requires bioassay testing, requires monitoring and reporting, and if the body is a sensitive environmental setting.

- Another Treatment System - a POTW or an industrial wastewater treatment system. This is the preferred discharge for treated groundwater. An advantage of a POTW is accessibility to sewer; an advantage of an industrial treatment system is that allowable contaminant concentrations may be higher than other discharge options.

Discharge Requirements

System design depends on the final disposition of the treated groundwater

- *Direct Use.* Must have very low effluent concentrations. Probably have to meet Federal drinking water standards.

- *Ground or Aquifer.* Strategically place recharge system to move plume. May be able to flush contaminants in the unsaturated zone. Any treated water reinjected outside the zone of influence should be at background concentrations

The Remediation Project

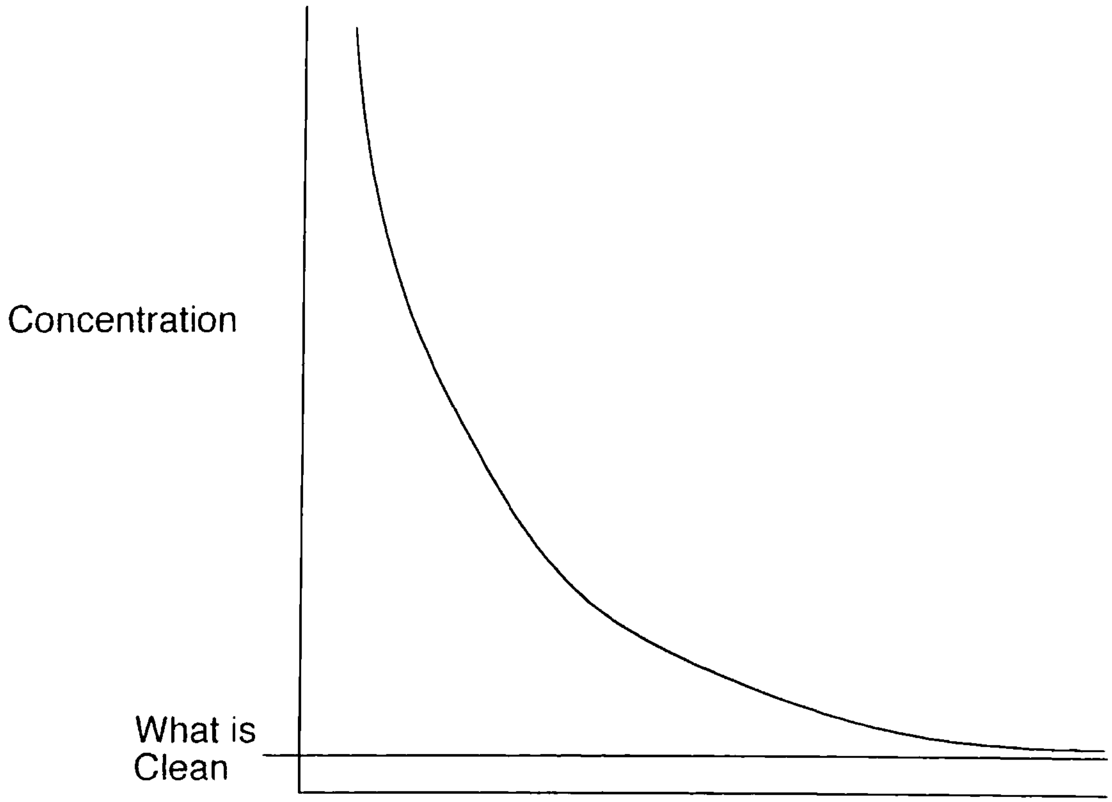
The influent concentration will change over the life of the project. The design must account for this cycle.

As we reach the last years of the project, the amount of contamination removed is minimal. May want to shut down the treatment system and actively monitor the groundwater until contaminant levels reach cleanup criteria by the biodegradation from naturally occurring bacteria.

How clean is clean? Established by:

- Risk assessment
- Drinking water standards
- Permit requirements
- Analytical detection limits

Life Cycle Concentration of a Remediation Project



The Design Methodology for the Remediation Project

- Time effect on influent parameters
- Capital costs
- Operator expense

Time Effect on Influent Parameters

Flow

The amount of water being <u>reused</u> may vary during the project

- Water may be reused to increase hydraulic head and remediate the plume
- Water may be reused to flush contaminants from the unsaturated zone
- Water may be reused for in situ contamination
- Drought may lower flow

Time Effect on Influent Parameters

Concentration

Removal of contaminants by the treatment system and the dilation effect of clean water entering the site produce a steady decline in the concentration of the groundwater

- The design of certain technologies are based on a minimum concentration. For example, some bioprocesses depend on the settling properties of the bacteria. However, as the influent concentration declines, the mean cell age increases and the bacteria loose their settling properties and may be difficult to separated from the process.

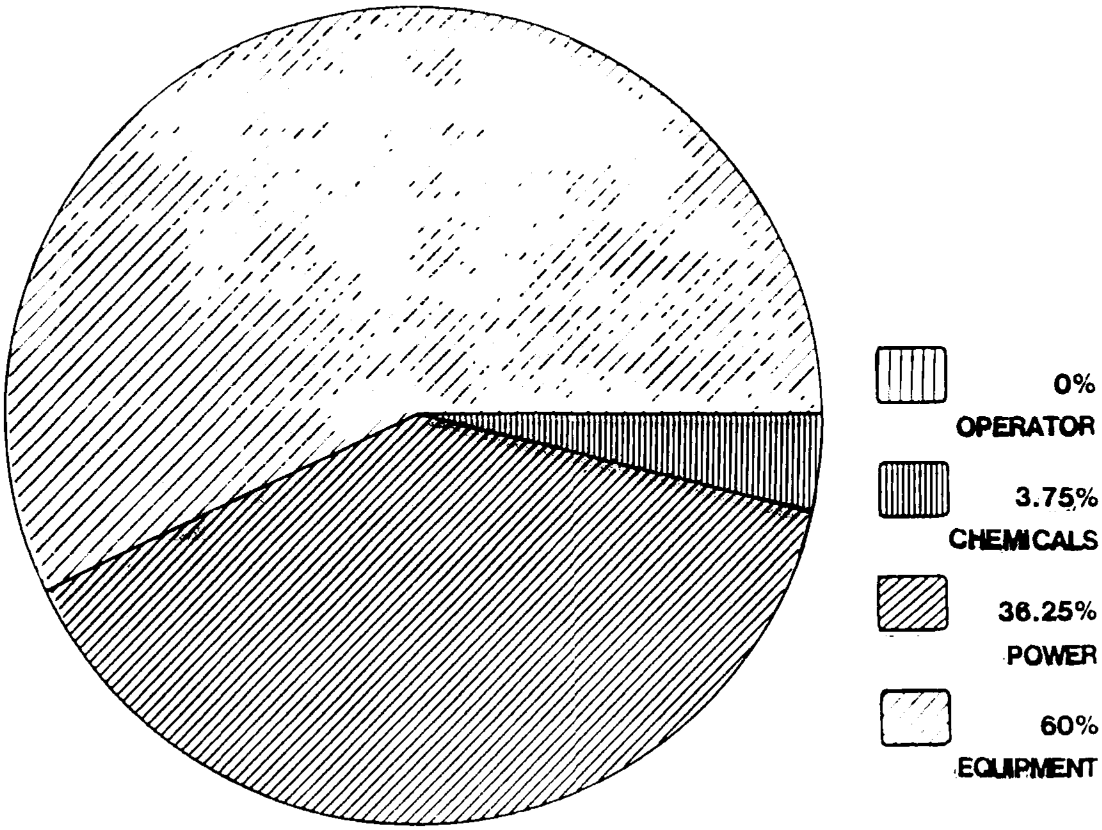
- Operating cost may decline as concentration declines.

One formula for calculating costs would be:

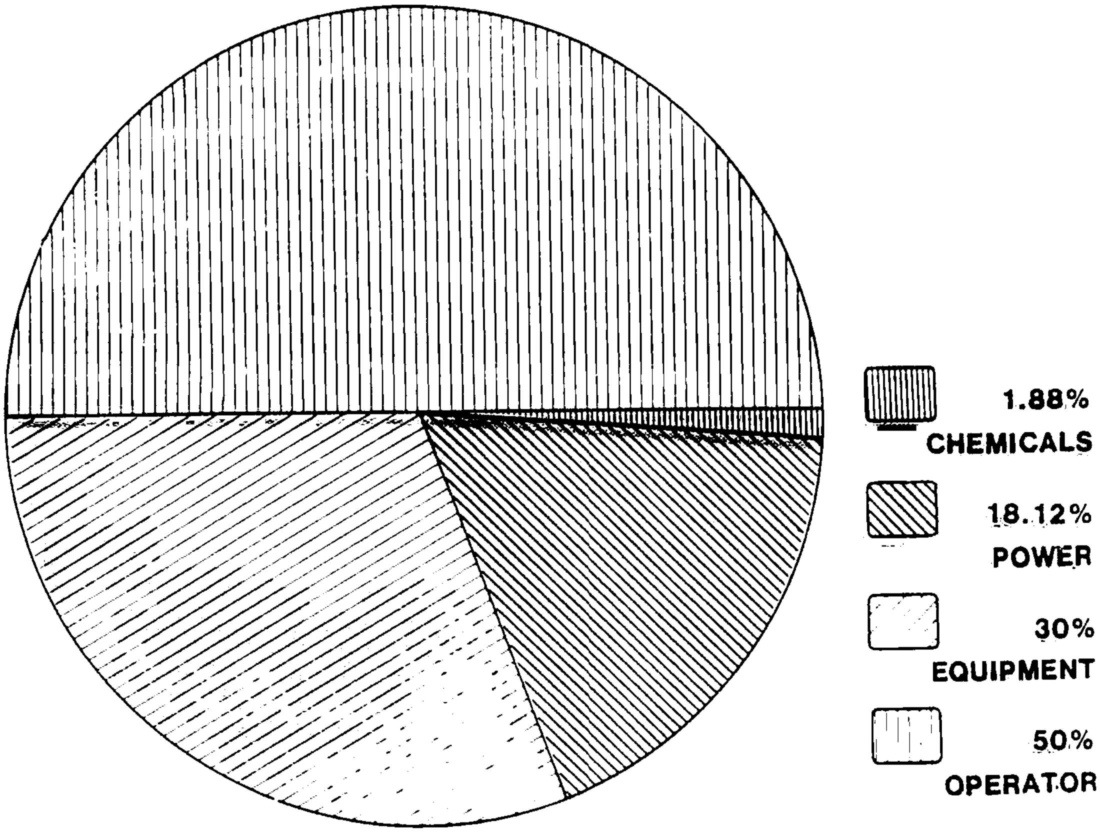
$$C = \frac{\text{Cap}}{[1 - (1 + i)^{-n}]/i}$$

where

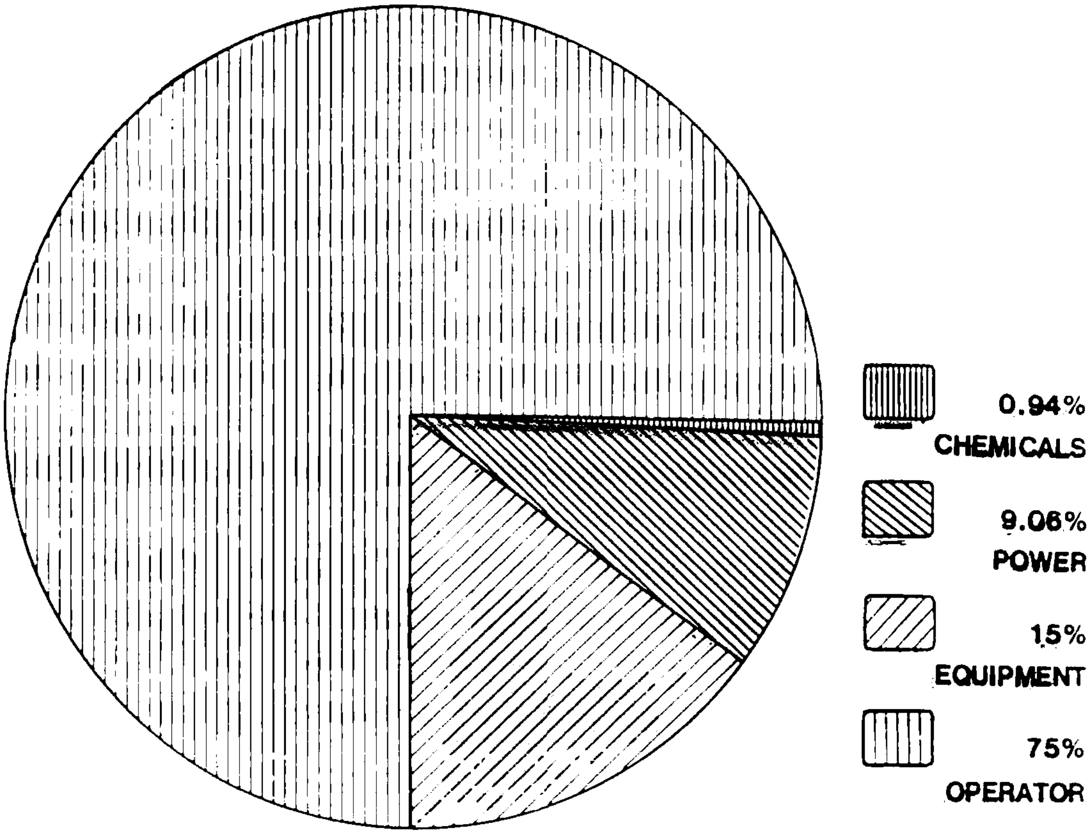
C is cost per time period *n*
Cap is capital cost
i is the interest rate
n is the period of time



Ratio of daily costs with no operator attention.



Ratio of daily costs with 8 hr/day of operator attention.



Ratio of daily costs with 24 hr/day of operator attention.

Air Stripping

A Mass Transfer Technology Whereby Volatile Organic Compounds (VOCs) are Transferred From the Liquid Phase to the Vapor Phase.

Advantages:

- Simplicity of Operation
- Low Capital Costs
- Low Operations and Maintenance Costs

Limitations:

- Strippable Compounds Such as Chlorinated Solvents, Lightweight Aromatics
- High Iron Content Usually Causes Fouling Which Lowers Removal Efficiency and Increases Maintenance Costs

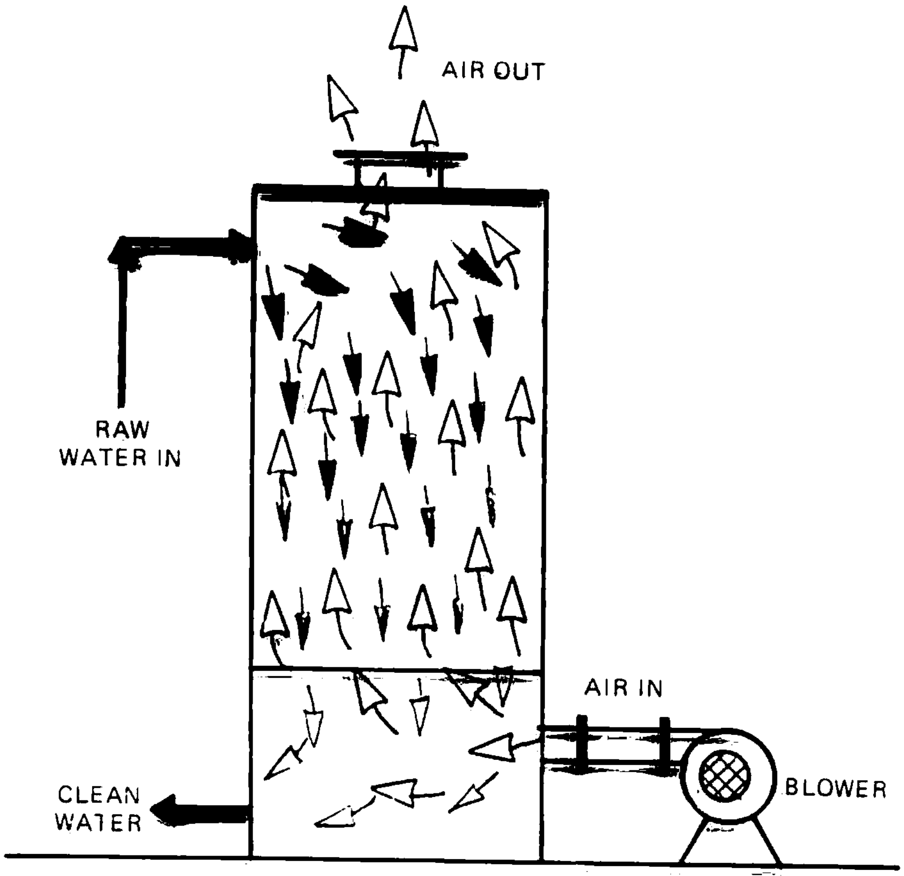
Costs:

- $0.05 to $0.25 / 1000 gal. Depending on Contaminants and No Air Stream Treatment
- Up to $2.00 / 1000 gal. with Air Stream-Treatment

Air Stripping

Packed Tower

In a Packed Tower Air Stripper, Air and Water are Run Counter-Current Through a Media, Called Packing, Which Enhances Air/Liquid Contact. The Packing a Greater Surface Area of Liquid to Air Creating a Greater Transfer of Volatile Organics From the Falling Water to the Rising Air. The Packing also Mixes the Water so the VOCs are not Limited by Internal Diffusion Through the Water.



Packed tower air stripper.

Air Stripping

Variables for Sizing a Packed Column:

- Tower Height
- Tower Cross-Section
- Air to Water Ratio
- Water Temperature

Tower Cross-Section Area is a Strong Function of Groundwater Flow Rate. The Area is Determined by the Flow Rate and the Liquid Loading Rate (Measure in GPM/ft^2.) Liquid Loading Rate Ranges From 15 to 35 GPM/ft^2.

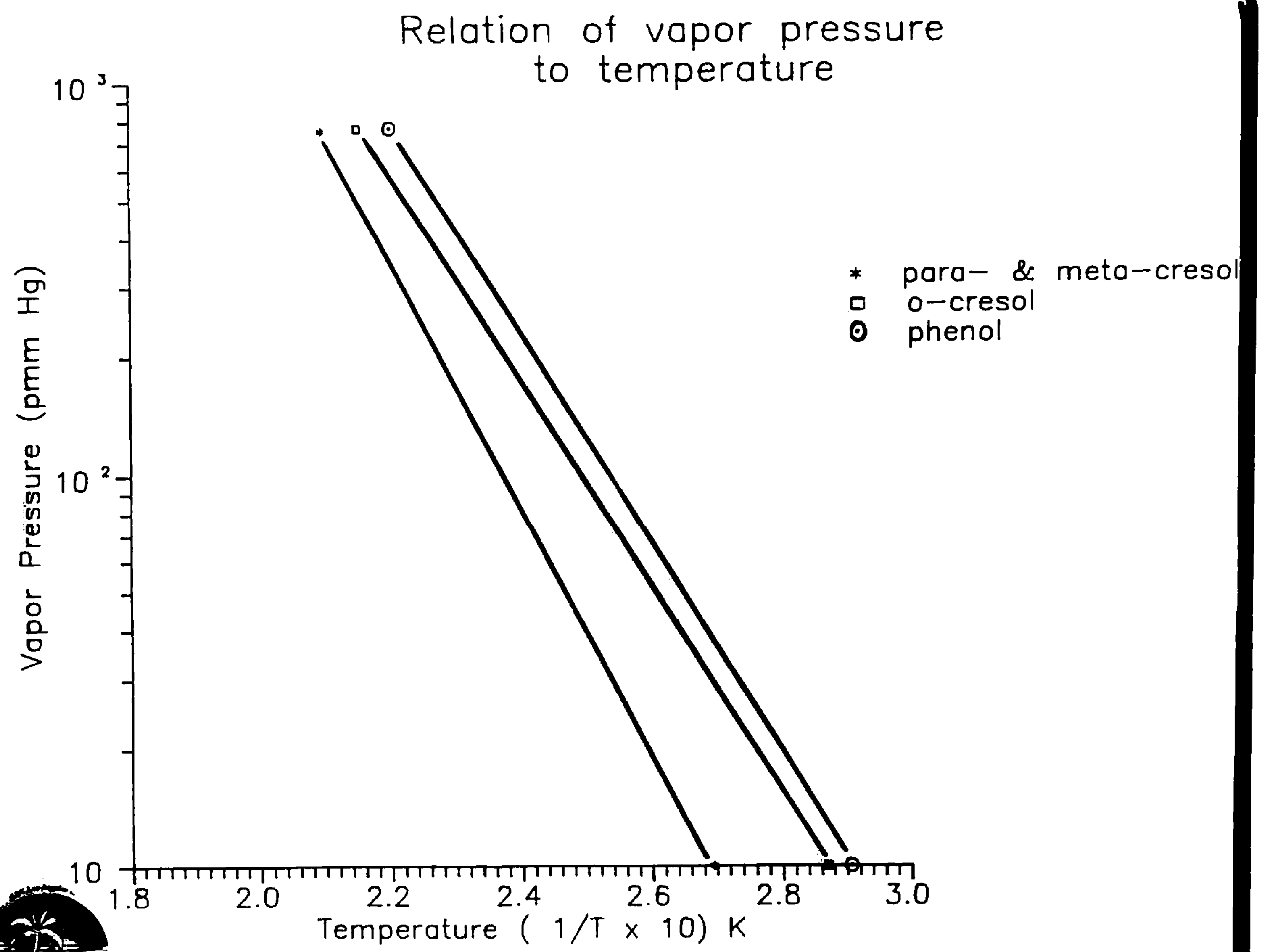
Tower Height is a Strong Function of Removal Efficiency. The Greater the Required Efficiency, the Taller the Tower.

Air Stripping

Air to Water Ratio is a Function of Contaminant Removal. The More Volatile a Component, the Lower the Volume of Air Required to Strip It.

Air : Water : : 10 : 1 to 200 : 1

Inlet Water Temperature Affects the Volatility of a Component. Groundwater Temperature May Be Increased by Pre-Heating Inlet Water or by Direct Stream Injection. Temperatures May Be Raised to 140 to 180°F. The Limitation of High Temperature is Higher Operating Cost.



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KEY ORGANIC CHEMICAL CHARACTERISTICS FOR TREATMENT SYSTEM DESIGN

(Primary Source: Groundwater Treatment Technology, with updates by K. Sullivan as found)

CHEMICAL	Solubility	Spec. Grav.	Henry's	Adsorp.	Bio. Deg.
1. Acetone	Infinite	0.79	0.05	Trace	D
2. Benzene	1780	0.88	240	76	D
3. Carbon Tetrachloride	800	1.59	1300	185	N,R
4. Chloroform	8000	1.48	170	1.6	N,D
5. Methylene Chloride	20,000	1.33	134	2.7	D
6. Chlorobenzene	500	1.11	228	190	D
7. Ethyl Benzene	152	0.87	323	210	D
8. Hexachlorobenzene	0.11***	2.04	33	NA	N
9. Ethylene Chloride	8690	1.24	61	4	R
10. 1,1,1-Trichloroethane	4400	1.34	200	155	N,R
11. 1,1,2-Trichloroethane	4500	1.44	41	159	R
12. Trichloroethylene	1100***	1.46	450	140	R
13. Tetrachloroethylene	150***	1.62	1100	345	N,R
14. Phenol	82,000**	1.07	0.1	31.2	D
15. 2-Chlorophenol	28,500	1.26	1.74	93.1	D
16. Pentachlorophenol	14	1.98	0.13	805	R,D
17. Toluene	515	0.87	320	147	D
18. Methyl Ethyl Ketone	353,000*	0.81	0.5	1.5	D
19. Naphthalene	32***	1.03	22	376	D
20 Vinyl Chloride	1.1***	0.91	359,000	Trace	R

Notes:
Solubility = mg/L @ 20 degC (* = 10 degC, ** = 15 degC, *** = 25 degC)
Specific Gravity (Water = 1.0)
Henry's Contant = atm-m^3water/m^3air
Adsorption Capacity = mg Compound/g Carbon (@ 500 ppb)
Adsorption Estimates supplied by Mr. Bob Byron, TIGG Corporation
Biodegradability (D=degradable, R=refractory, N=non-degradable)

N.B. Most values are derived for ideal, 'clean', single-compound solutions. Multi-contaminant systems may behave differently

Revised 6/87

The mass transfer equations for an air/water stripping system are:

$$Z = \mathrm{HTU} \times \mathrm{NTU}$$

$$\mathrm{HTU} = L'/K_{\mathrm{la}}$$

$$\mathrm{NTU} = (R/(R-1)) \times \ln\left[((C_{\mathrm{inf}}/C_{\mathrm{eff}}) \times (R-1) + 1)/R\right]$$

where:

$$R = (H \times G)/(L' \times P)$$

and

HTU = Height of transfer unit (feet)
NTU = Number of transfer units (unitless)
H = Henry's law constant (atm)
G = Gas loading rate (cfm)
L' = Liquid loading rate (gpm/sq. ft.)
P = Operating pressure (atm)
Z = Packing height (feet)
C_{inf} = Influent concentration (μg/l)
C_{eff} = Effluent concentration (μg/l)
K_{la} = Overall mass transfer coefficient (sec^{-1})
R = Stripping factor (unitless)

(Note: Unit conversion factors are not shown in the above equations. Units should be consistent.)

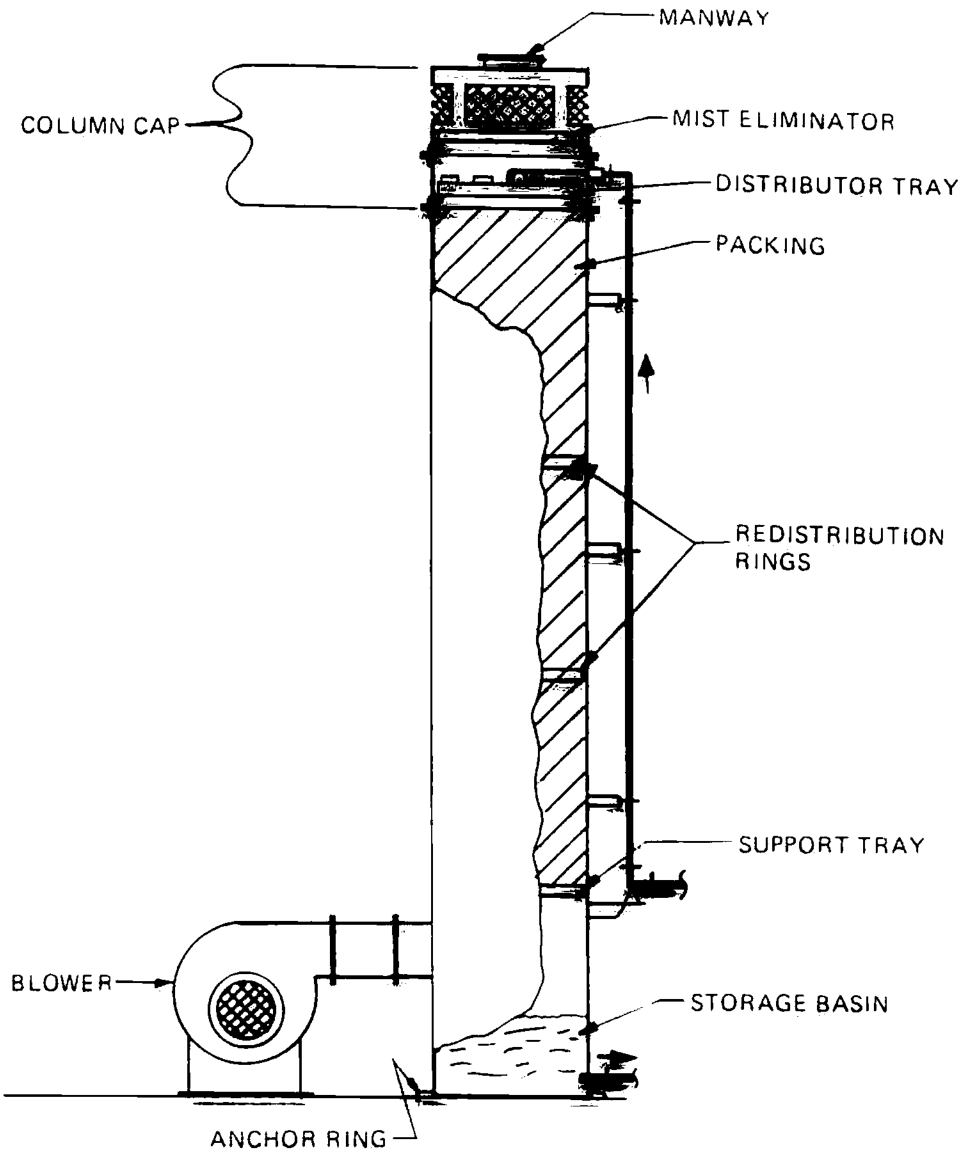
Air Stripping

The Key Variables to Define in the Mass Transfer Equations Are:

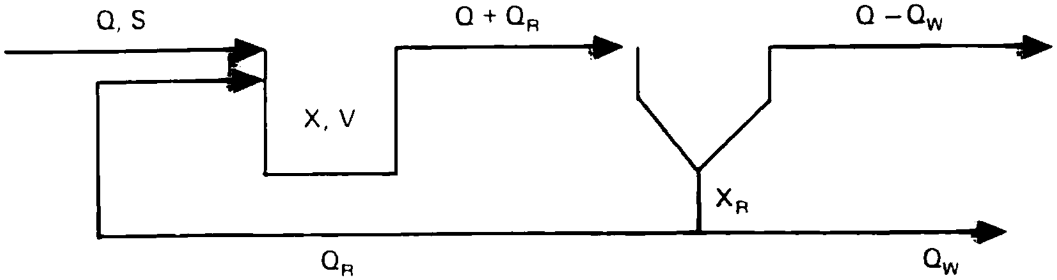
- *Henry's Law Constant (H)*
- *Overall Mass Transfer Coefficient (K_{ea})*

The Henry's Law Constant Can Be Obtained From Reference Books.

The Mass Transfer Coefficient is a Function of Tower Design and Packing Type. It Expresses the Overall Efficiency of the Tower. Best to Select a Mass Transfer Coefficient Based on Field Data From a Pilot Test. Testing Should Cover a Range of Liquid Loading Rates and Air to Water Ratios While Measuring the Resulting Effluent Concentration. The Mass Transfer Equations are Solved for K_{ea}.



Packed tower components.

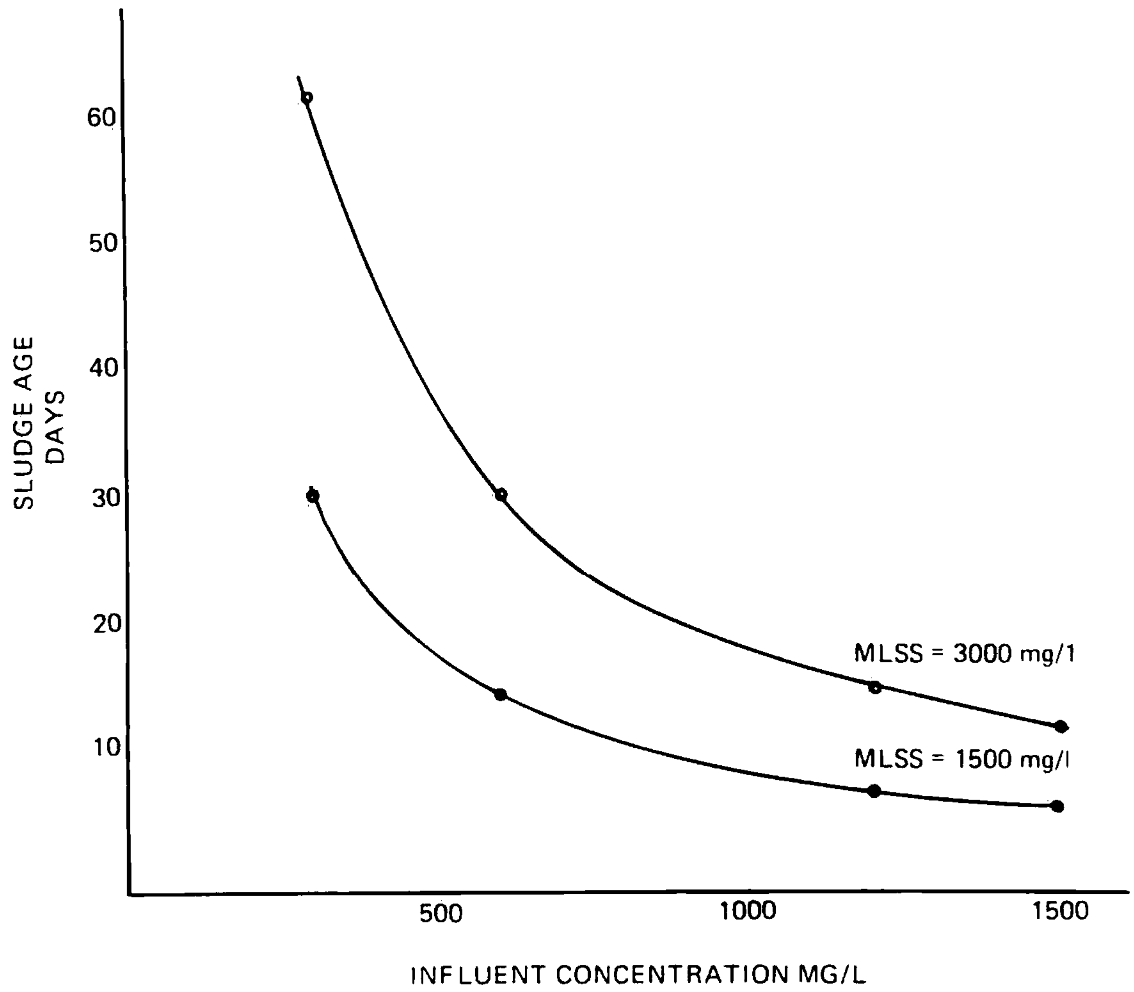


Q = Flow
Q_R = Recycle Flow
Q_W = Sludge Wastage Flow
X = Mixed Liquor Suspended Solids (MLSS)
X_R = Clarifier Underflow Solids Concentration
X_E = Effluent Solids Concentration
V = Volume of Aeration Basin
S = Organic Concentration

Activated sludge treatment system.

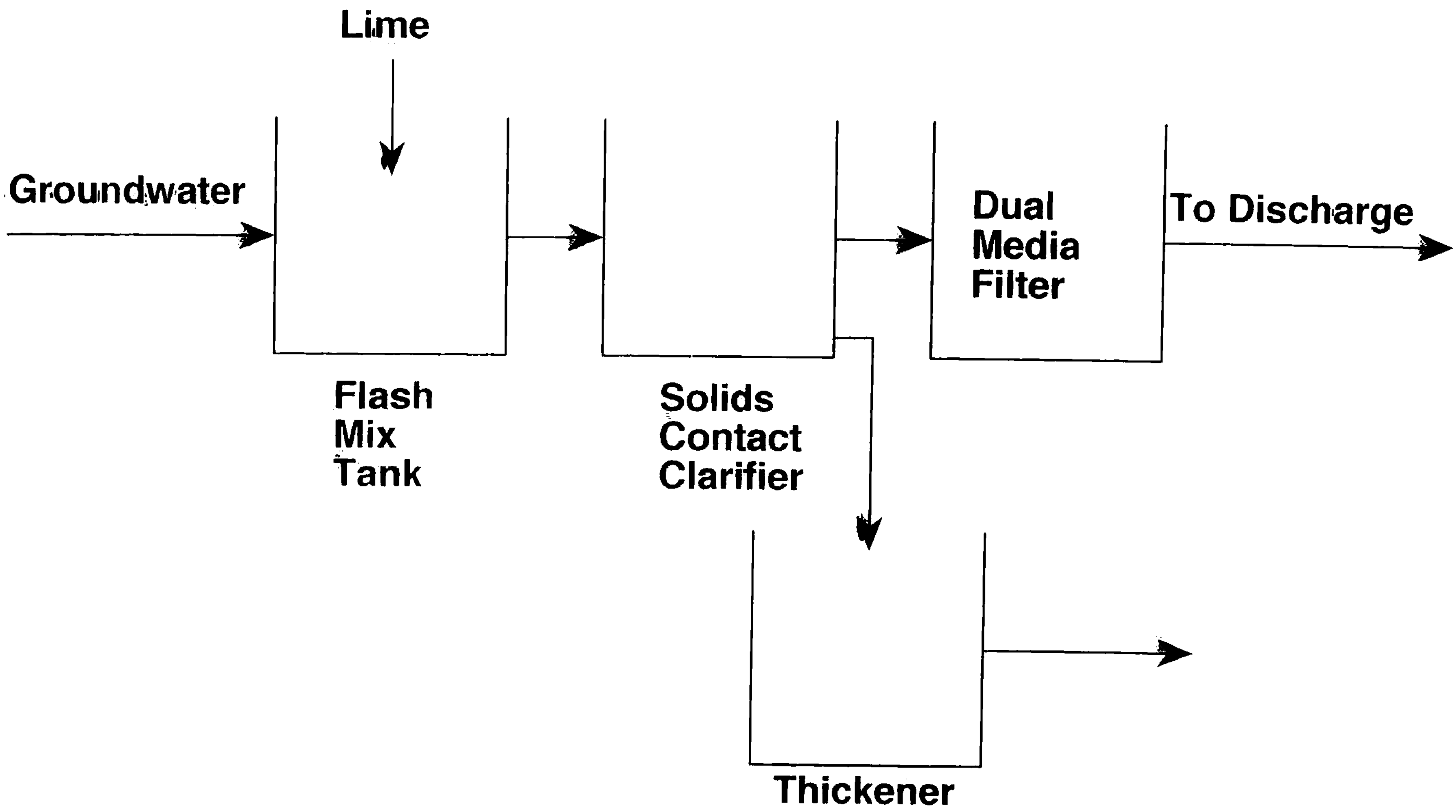
sludge age

$$A = (X \times V)/(Q \times S \times Y)$$



. Sludge age with life cycle influent concentrations.

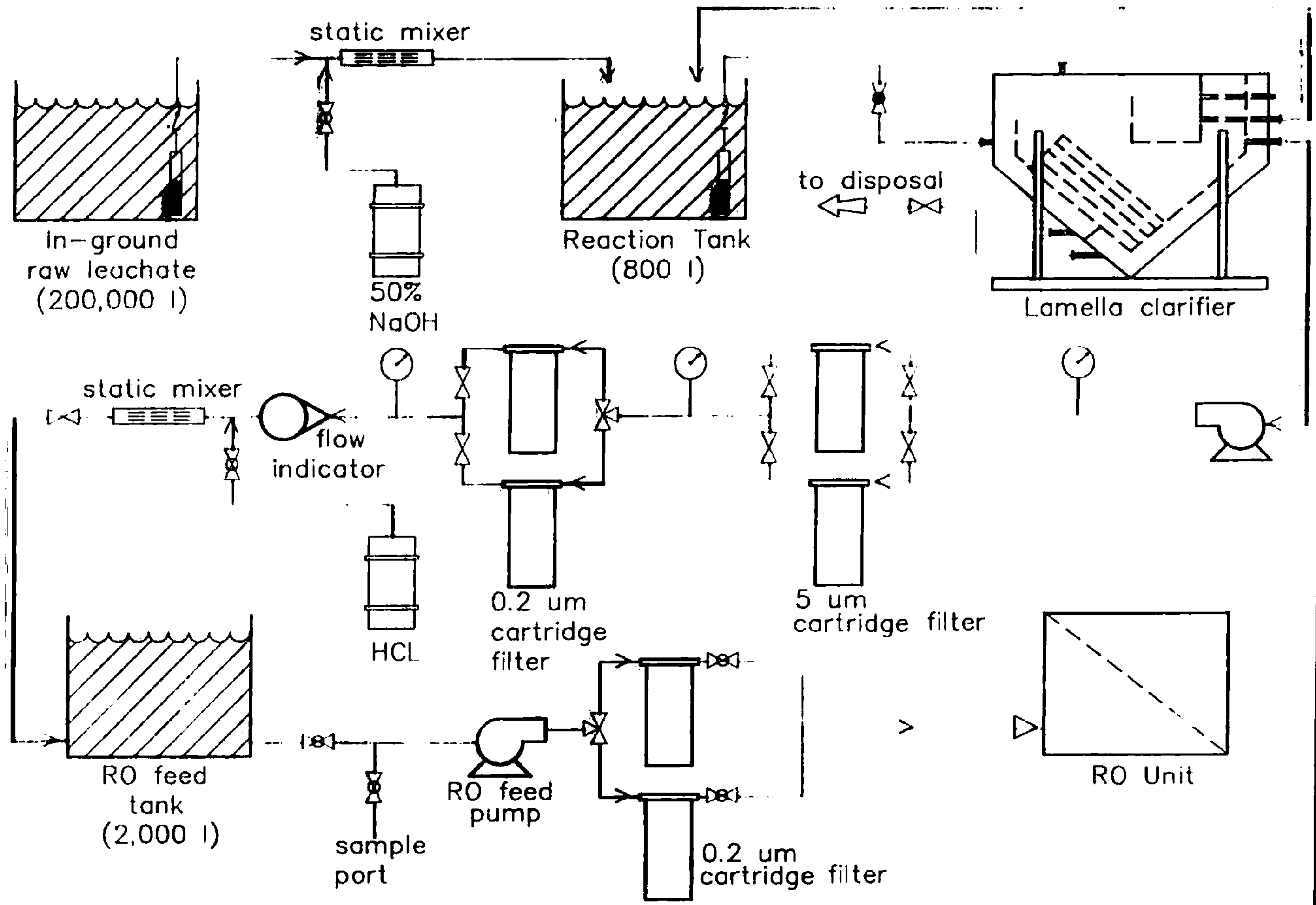
Treatment Plant Design for a Heavy Metal



Reverse Osmosis

The Technology Uses A Semi-Permeable Membrane to Separate a Solute, Chemical Compound or Ion, From a Solvent or Groundwater. The Solvent Flows Through the Membrane, Under a Hydrostatic Pressure Greater Than the Osmotic Pressure, While the Larger Compounds are Rejected and Retained Behind the Membrane.

The Inlet Stream is Separated into Two Outlet Streams: the Permeate Which Contains the Treated Groundwater and the Retentate or Concentrate Which Contains Elevated Concentrations of the Chemicals of Concern. The Volume of the Retentate is Much Less Than the Inlet Volume and the Concentration of the Chemicals of Concern are Greater Than the Inlet Concentration; Therefore, Reverse Osmosis is a Volume Reduction Technology.



Reverse osmosis (RO) pretreatment system

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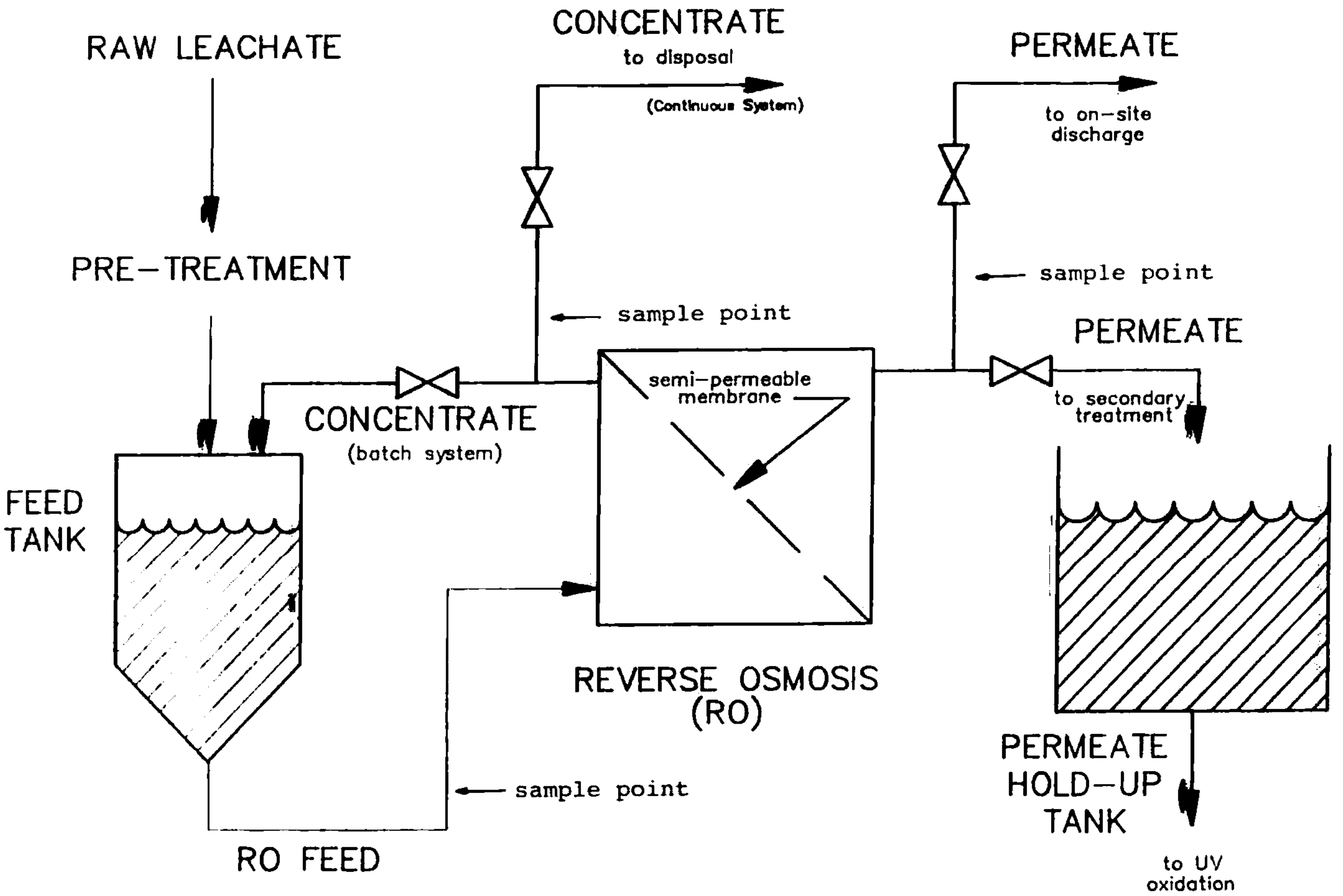
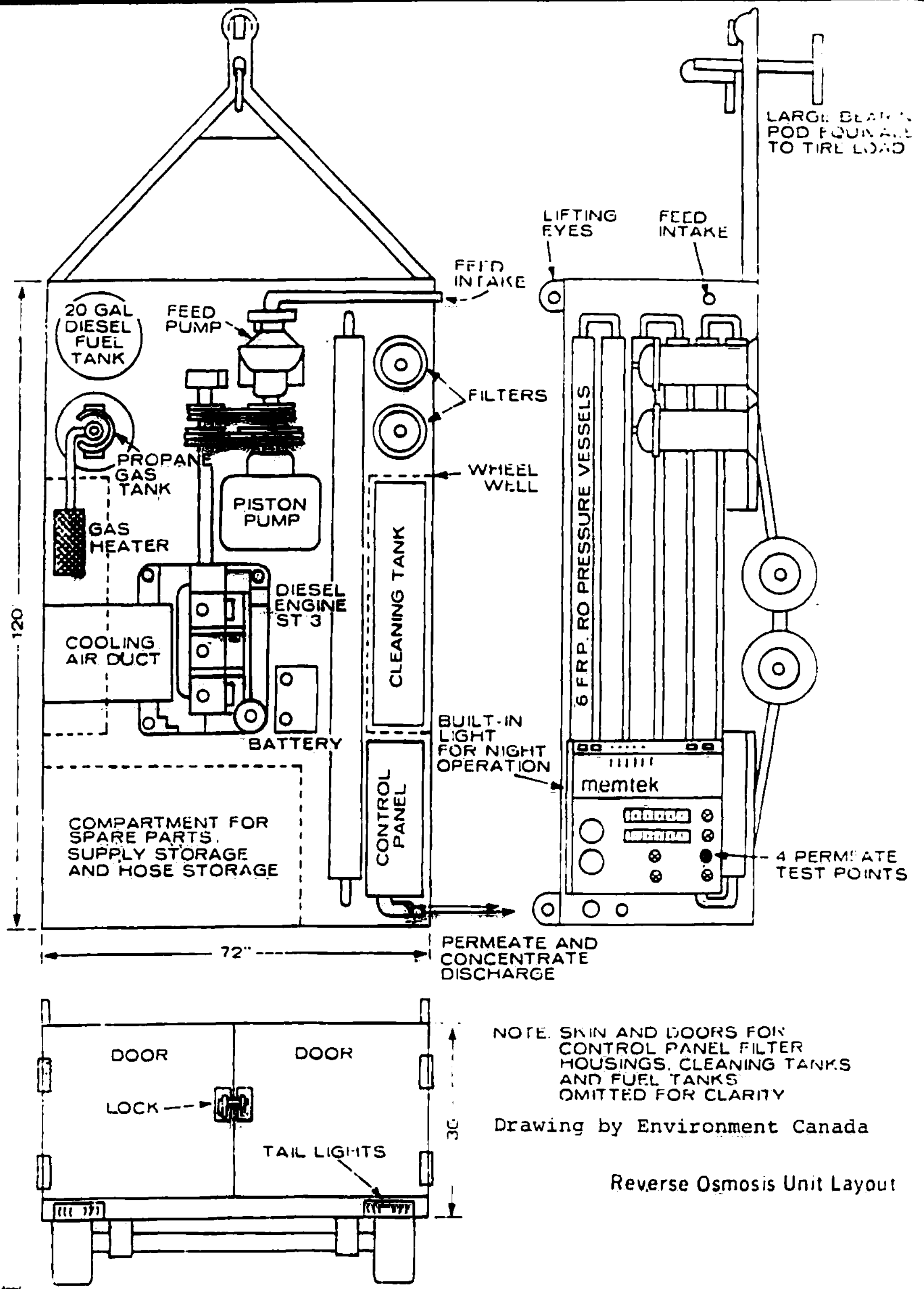


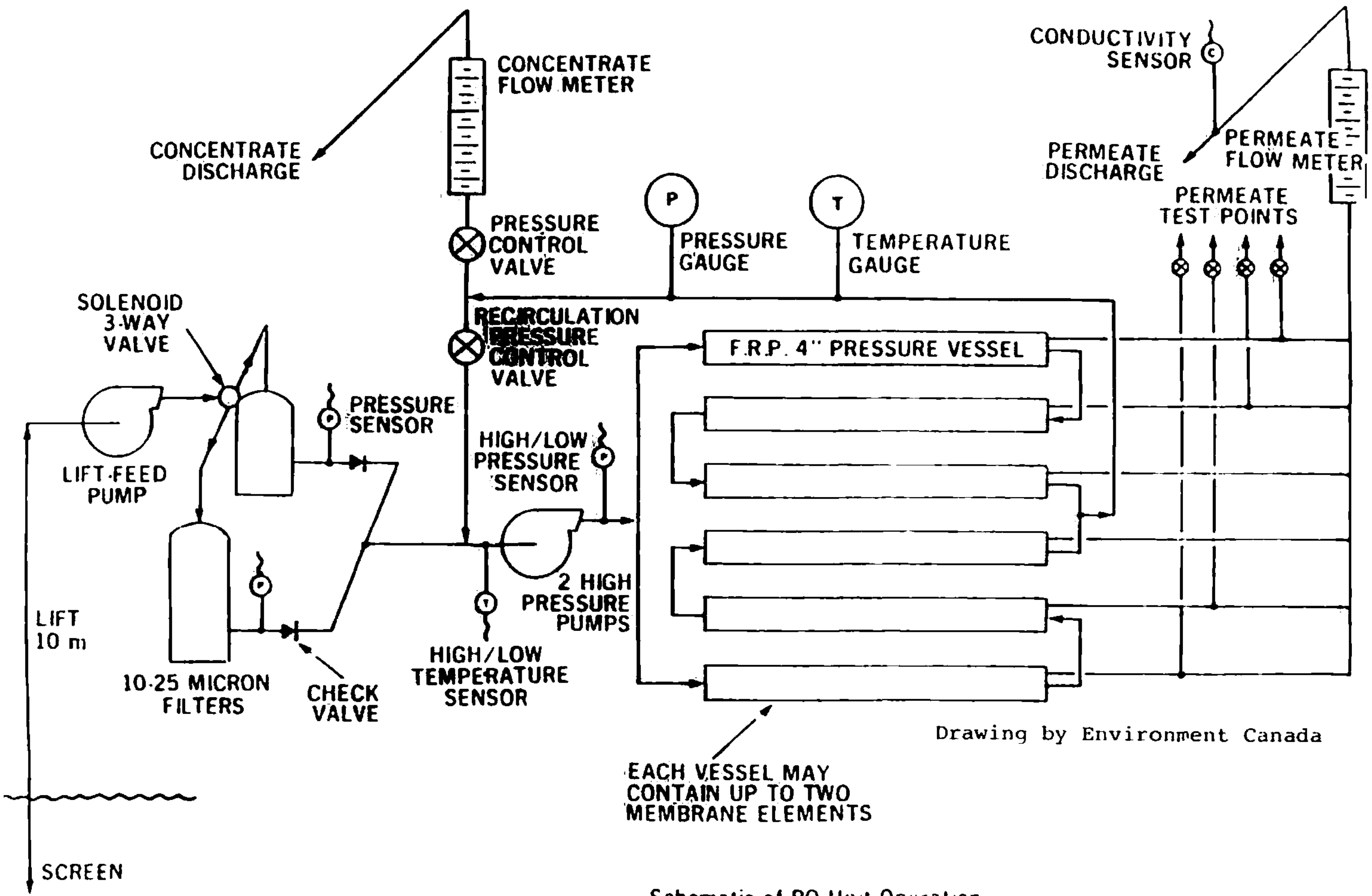
Reverse osmosis (RO) treatment system



NOTE. SKIN AND DOORS FOR CONTROL PANEL FILTER HOUSINGS, CLEANING TANKS AND FUEL TANKS OMITTED FOR CLARITY

Drawing by Environment Canada

Reverse Osmosis Unit Layout



Drawing by Environment Canada

Schematic of RO Unit Operation

Reverse Osmosis

Membrane Separation Efficiency (E), in Terms of Chemical Rejection, is:

$$E = 1 - (C_P/C_F)$$

Where: C_P = Chemical Concentration in Permeate
C_F = Chemical Concentration in Feed

Groundwater Recovery Fraction (R) is:

$$R = Q_P/Q_F$$

Where: Q_P = Permeate Flow
Q_F = Feed Flow

Reverse Osmosis

Advantages:

- Removes High Levels of Inorganic Salts and Heavy Metals
- Removal of Large Non-Polar Organic Compounds
- Removal of Most Polar Organic Compounds
- Can Be Used to Recycle Some Compounds

Limitations:

- Does Not Destroy Chemicals of Concern
- Does Not Remove All Organics
- Membrance Fouling Reduces Flow of Permeate, May Reduce Separation Efficiency, and Increase Operating and Maintenance Costs
- Groundwater May Require Pre-Treatment and System May Have to be Accurately Operated to Reduce Fouling

Reverse Osmosis

Operation and Maintenance Costs:

- Membrance Cleaning
- Membrance Replacement
- Unit Maintenance
- Monitoring
- Power Consumption

O & M Cost per 1000 Gallons to Remove THM from Groundwater:

$0.68 for 700 GPM
$0.55 for 1700 GPM
$0.79 for 700 GPM

Total Cost per 1000 Gallons to Remove Agricultural Chemicals from Groundwater:

Flow	RO	GAC	Air Stripping
7	$5.00	$4.05	$1.30
70	$3.30	$2.05	$0.57
700	$1.95	$1.00	$0.31

PERCENT REJECTION OF CONTAMINANTS BY REVERSE OSMOSIS MEMBRANES

	UOP		DSI		TORAY		FILMTEC	
	Mean	n	Mean	n	Mean	n	Mean	n
VOLATILE ORGANIC (VOA) ORGANICS								
Methylene Chloride	35.7	12	48.9	11	46.9	7	50.5	11
Acetone	45.9	11	44.5	10	38.3	6	73.8	11
1,1-Dichloroethene	56.7	9	62.7	8	61.8	7	74.7	9
1,1-Dichloroethane	57.2	12	64.7	11	64.3	8	88.2	11
t-1,2-Dichloroethene	10.7	12	28.2	11	30.5	8	47.4	11
Chloroform	ND	11	ND	11	ND	8	ND	11
1,2-Dichloroethane	41.0	12	52.3	12	53.7	9	75.3	11
1,1,1-Trichloroethane	76.9	12	85.2	12	85.7	9	93.3	11
Carbon Tetrachloride	42.9	4	54.1	3	43.2	3	59.3	3
Bromodichloromethane	67.0	10	75.6	10	62.3	7	91.6	10
1,2-Dichloropropane	3.5	3	43.7	2	98.3	1	72.5	1
Cis-1,3-Dichloropropane	0	3	32.7	3	27.5	3	24.7	3
Trichloroethene	43.8	12	59.9	12	50.9	9	59.8	11
Benzene	53.5	12	57.9	12	68.2	9	83.9	11
t-1,2-Trichloroethane								

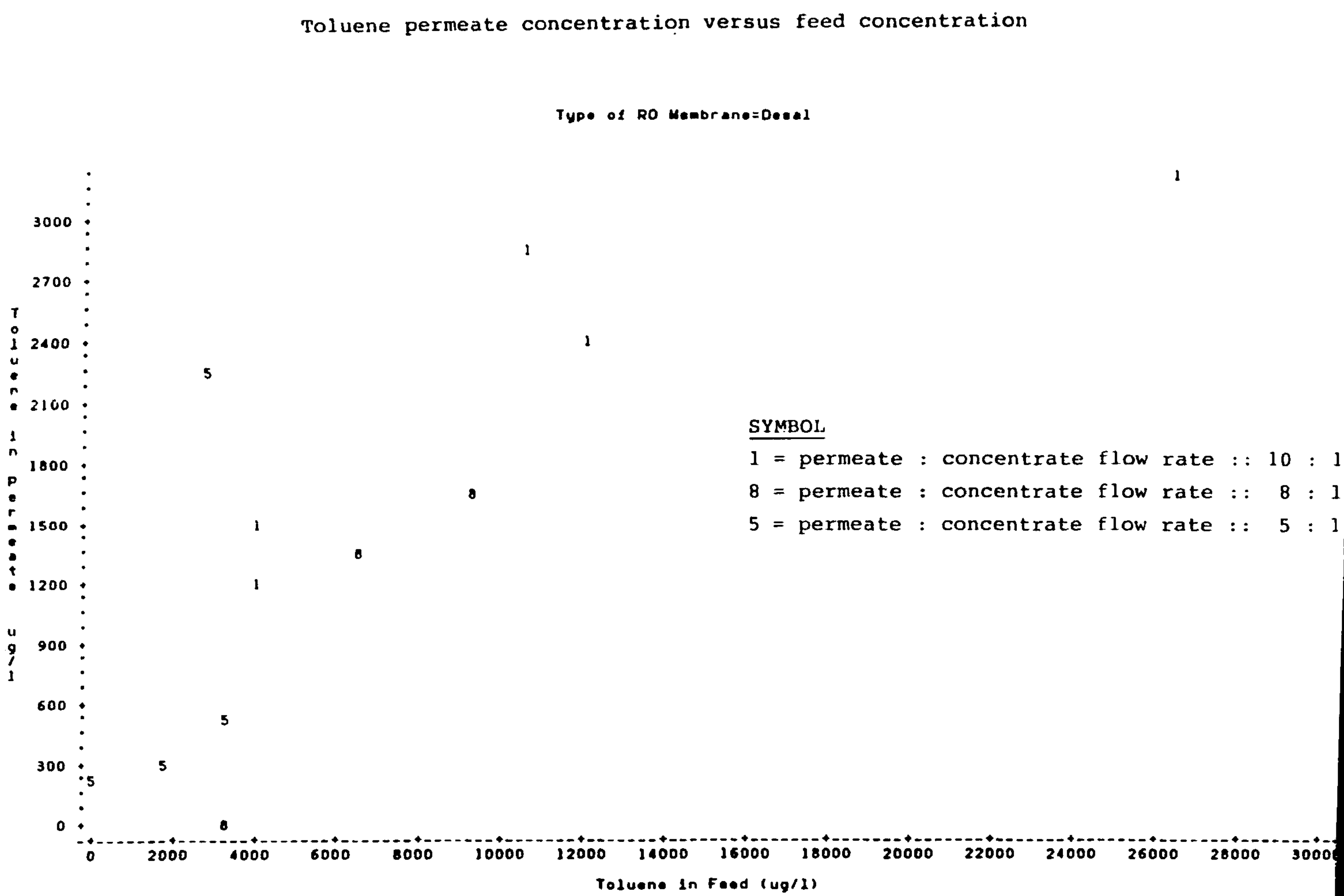
PERCENT REJECTION OF CONTAMINANTS BY REVERSE OSMOSIS MEMBRANES

	UOP		DSI		TORAY		FILMTEC	
	Mean	n	Mean	n	Mean	n	Mean	n
VOLATILE ORGANIC (VOA) ORGANICS								
t-1,3-Dichloropropane	ND	10	ND	11	ND	7	ND	11
Dibromochloromethane								
Methyl Isobutyl Ketone	77.7	11	85.4	11	71.6	8	73.7	11
Bromoform	74.9	10	91.5	9	69.1	8	99.5	9
Tetrachloroethene	78.5	12	61.4	12	46.2	9	66.4	11
Toluene	54.2	12	68.1	12	67.7	9	83.7	11
Chlorobenzene	36.4	12	55.5	11	59.1	8	76.7	10
Ethylbenzene	66.1	11	74.3	11	74.6	9	94.9	10
meta- and para-Xylene	74.2	11	83.9	10	84.6	7	96.3	9
ortho-Xylene	71.9	11	83.2	9	83.4	7	96.6	9
SEMI-VOLATILE (BNA) ORGANICS								
Phenol	54.5	10	55.7	10	52.5	7	72.1	10
Benzyl Alcohol	42.0	2	25.0	2	25.0	2	28.0	3
1,2-Dichlorobenzene	64.4	10	91.7	10	73.3	7	87.9	10
2-Methylphenol	47.3	7	73.4	6	49.0	7	77.8	9
4-Methylphenol	78.6	10	57.4	10	59.8	7	89.8	10
Isophorone	83.9	4	79.9	5	75.0	4	83.9	4
2,4-Dimethylphenol	72.3	10	69.2	10	64.0	7	88.5	10
Benzoic Acid	67.8	7	81.9	8	76.3	5	86.4	8
Naphthalene	74.2	10	80.6	9	70.2	7	88.9	9
2-Methylnaphalene	85.0	5	60.8	4	57.7	2	92.6	5

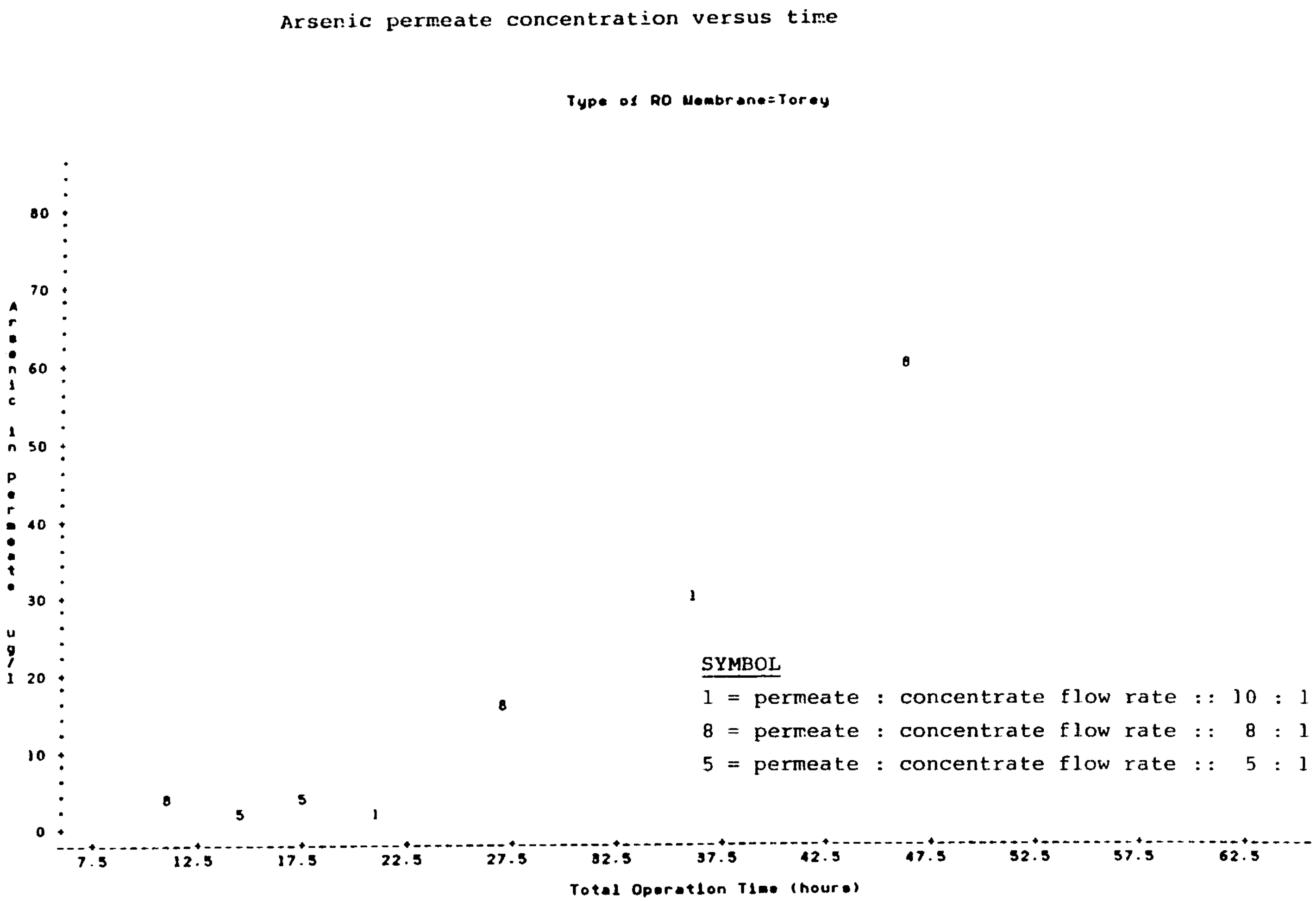
PERCENT REJECTION OF CONTAMINANTS BY REVERSE OSMOSIS MEMBRANES

	UOP		DSI		TORAY		FILMTEC	
	Mean	n	Mean	n	Mean	n	Mean	n
Bis(2-Ethylhexyl)phthalate	78.4	10	76.4	8	54.9	6	71.1	9
Di-n-octylphthalate	50.0	6	41.7	6	63.7	3	52.3	10
Di-n-butylphthalate	37.5	2	25.0	2	56.2	6	37.5	2
HEAVY METALS								
Antimony	89.6	6	89.6	6	75.8	6	85.7	6
Arsenic	95.4	8	85.0	8	61.5	6	98.6	8
Beryllium	ND	1	ND	1	ND	1	ND	1
Cadmium	ND	9	ND	9	ND	6	ND	9
Chromium	ND	9	ND	9	ND	6	ND	9
Copper	84.4	1	84.4	1	84.4	1	84.4	1
Lead	10.3	9	16.9	8	10.0	8	29.1	7
Mercury	ND	1	ND	1	ND	1	ND	1
Nickel	98.3	9	92.8	9	79.6	6	88.2	9
Selenium	1.7	3	19.4	3	ND	6	15.0	4
Silver	ND	9	ND	9	ND	6	ND	9
Thallium	ND	8	ND	8	ND	6	ND	8
Zinc	45.4	9	33.6	9	27.1	6	53.3	9

ND - Means not detected.

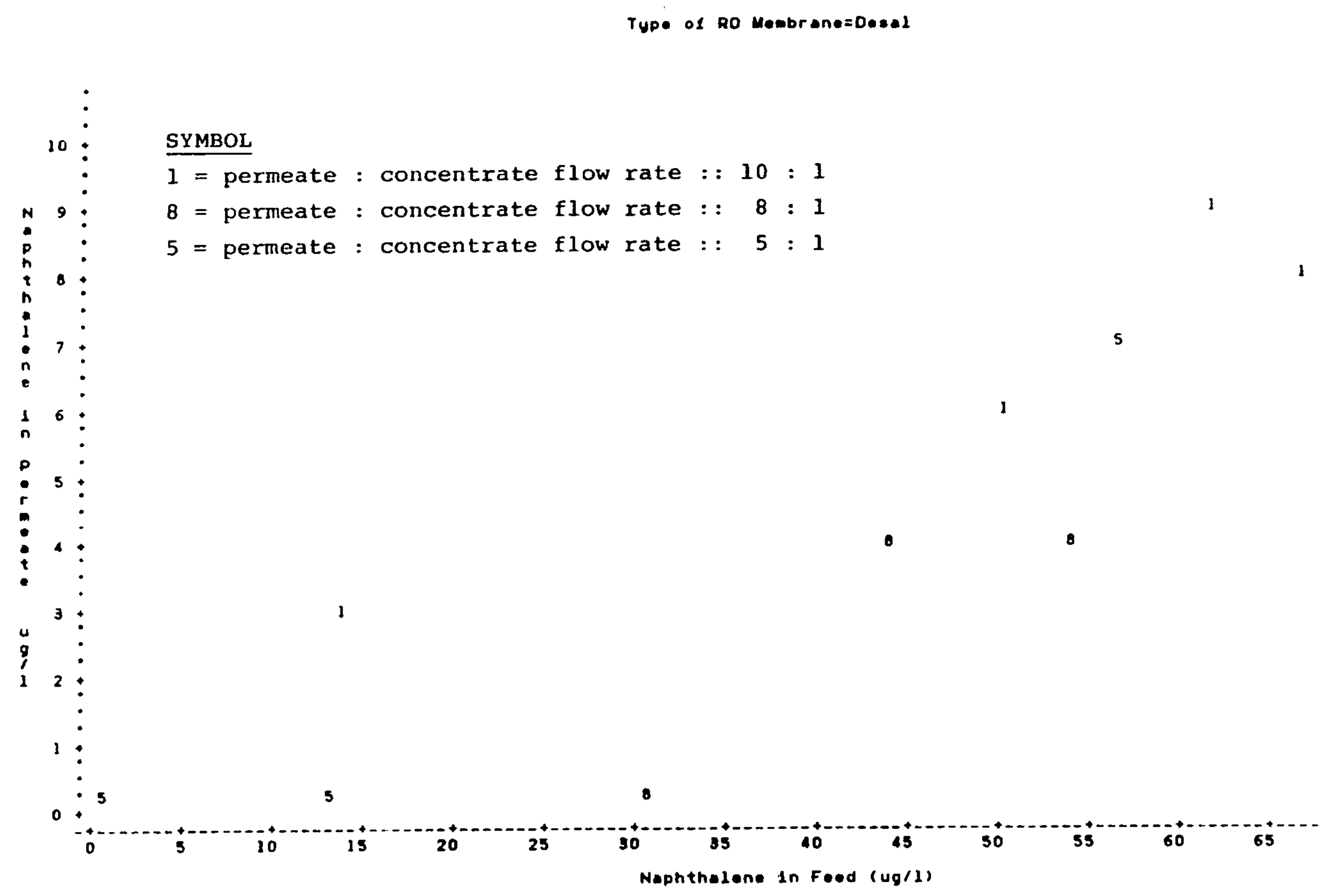


Toluene permeate concentration versus feed concentration
Type of RO Membrane=Desal
Toluene in permeate ug/l
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000 22000 24000 26000 28000 30000
Toluene in Feed (ug/l)
SYMBOL
1 = permeate : concentrate flow rate :: 10 : 1
8 = permeate : concentrate flow rate :: 8 : 1
5 = permeate : concentrate flow rate :: 5 : 1

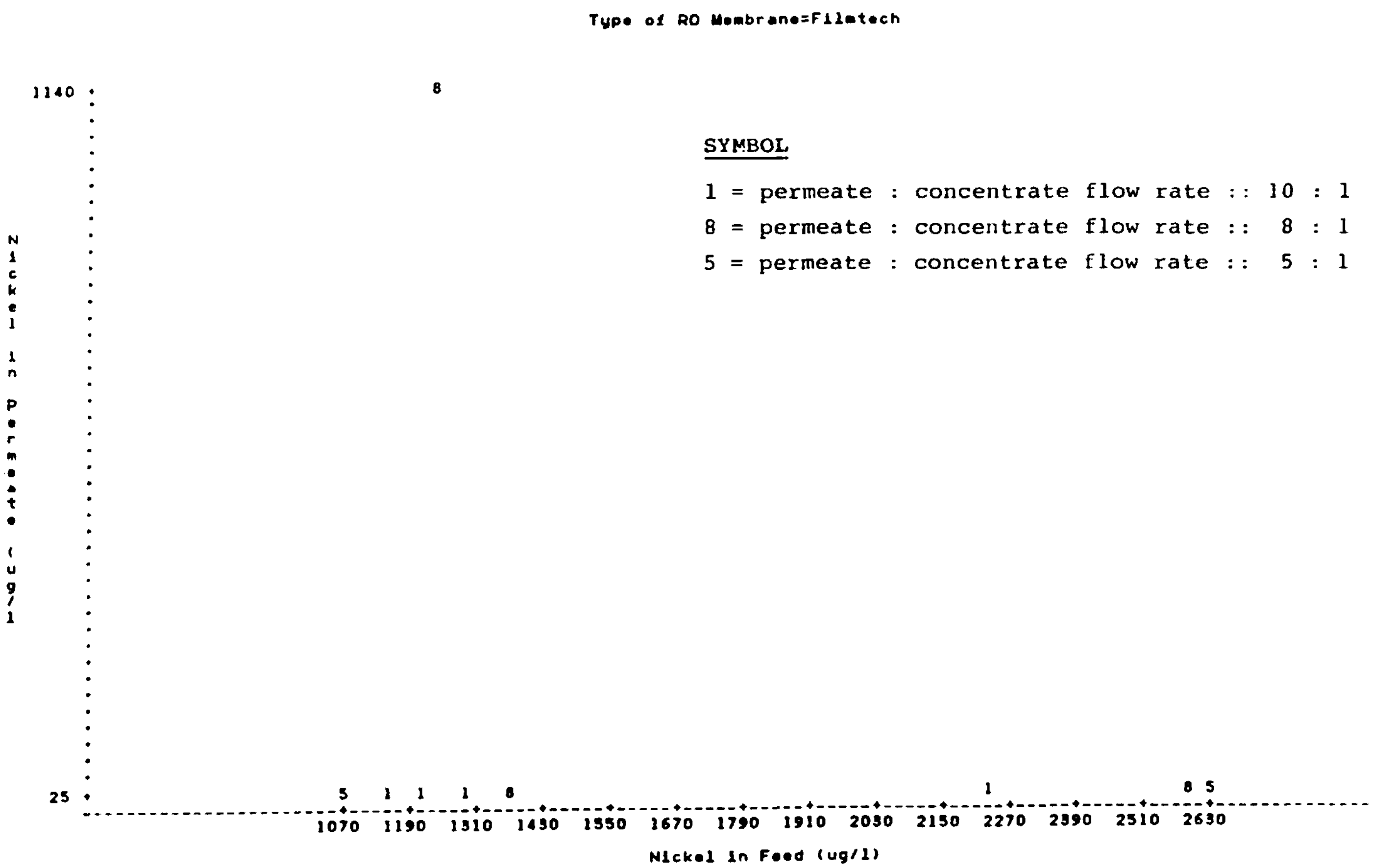


Arsenic permeate concentration versus time
Type of RO Membrane=Torey
Arsenic in permeate ug/l
80
70
60
50
40
30
20
10
0
7.5
12.5
17.5
22.5
27.5
32.5
37.5
42.5
47.5
52.5
57.5
62.5
Total Operation Time (hours)
SYMBOL
1 = permeate : concentrate flow rate :: 10 : 1
8 = permeate : concentrate flow rate :: 8 : 1
5 = permeate : concentrate flow rate :: 5 : 1

Naphthalene permeate concentration versus feed concentration



Nickel permeate concetration versus feed concentration



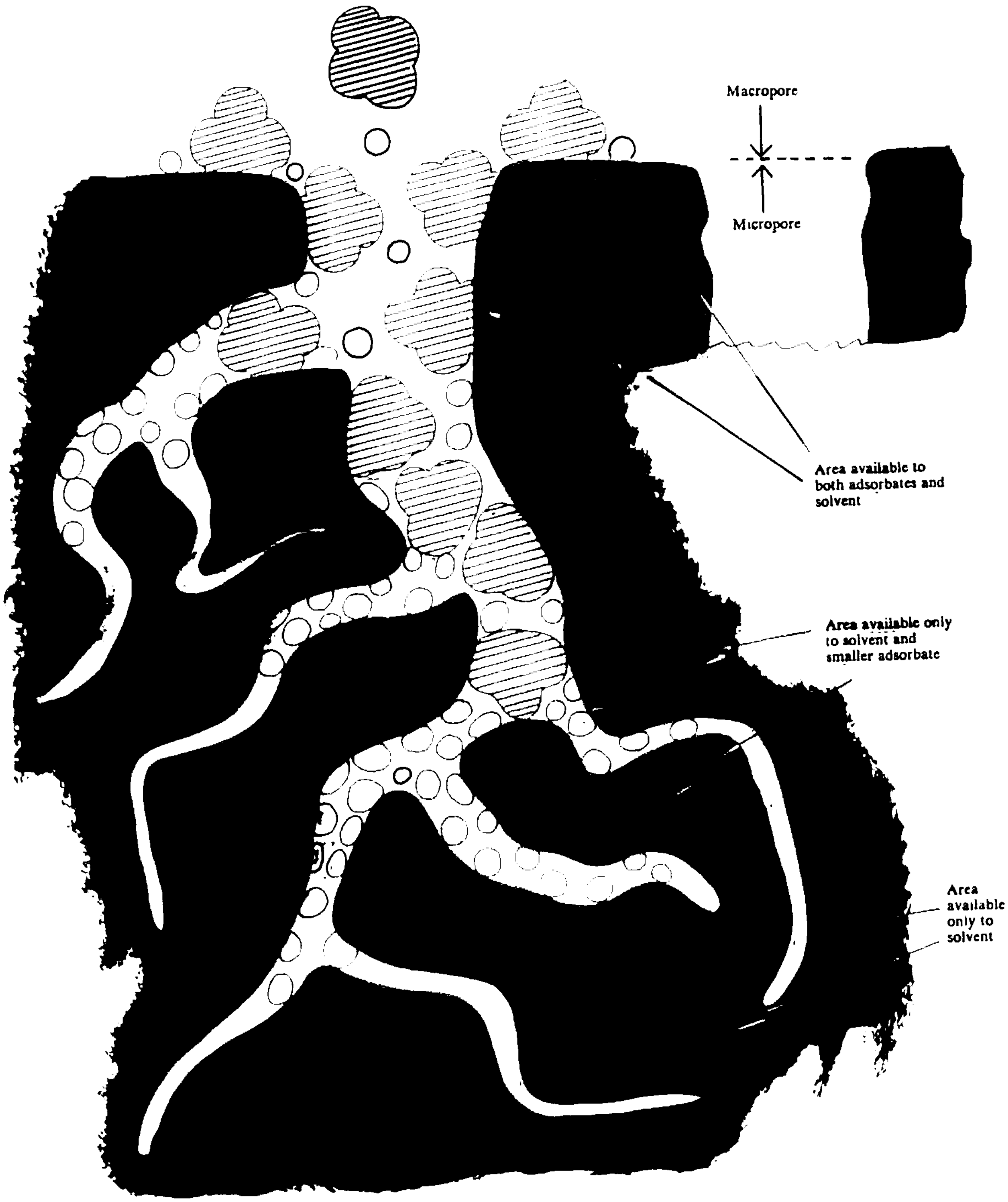
Activated Carbon

Technology uses a variety of carbons to selectively adsorb a wide range of organic and certain inorganic compounds. Cost of treatment ranges from $0.38 to $2,52 / 1000 gal.

Source materials are bituminous coal, coconut shell, lignite, pump mill residue and wood. The surface area, on which adsorption takes place, varies by carbon type but ranges between 500 and 1400 meters 2/gm.

Most of the surface area of carbon is part of the internal structure. This structure is comprised of macropores and micropores.

CONCEPT OF MOLECULAR SCREENING IN MICROPORES



Activated Carbon

Adsorption is a 3 step mechanism

- External diffusion of compounds through the liquid to the carbon particle
- Internal diffusion through the macropores
- Adsorption to the surface

Molecular Screening

Many of the micropores are only large enough for small molecules. The effective surface area for adsorption exists only in pores that a molecule can enter. Therefore, the surface area for adsorption of a particular compound depends on its size and the available surface area accessible to it.

The adsorptive properties of a particular carbon are expressed in terms of its compounds (adsorbate), such as iodine, methylene blue, and molasses.

Activated Carbon

Freundlich Isotherm Equation

$x/M = KC^{1/n}$ or

$\log x/M = 1/n \log C + \log K$

On log/log paper

1/n	=	slope of the line
K	=	y intercept
x/M	=	is the ordinate of the graph
C	=	is the abscissa

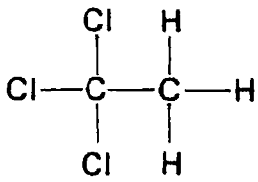
Activated Carbon

Calculation of Carbon Capacity

To calculate the capacity of carbon for a particular species, an adsorption isotherm test is performed. A fixed volume of water containing a chemical of concern is mixed with a known weight of carbon. After equilibrium is reached, the carbon is removed and the residual chemical concentration, C, is measured. The amount of adsorbed chemical, x, is the initial concentration, C_o, minus the residual, or $x=C_o-C$. If M is the weight of the carbon, then x/M = the amount adsorbed per weight of carbon (mg/g), at a specific C_o. The test is repeated several times for different carbon doses, M.

COMPOUND: 1,1,1-Trichloroethane

STRUCTURE:



FORMULA: $C_2H_3Cl_3$ **MOL. WT.** 133.41

FREUNDLICH PARAMETERS	pH		
	5.3		
K	2.48		
1/n	0.34		
Corr. Coef. r	0.97		
INITIAL CONC. mg/l	ADSORPTION CAPACITY, mg/gm		
1.0	2.5		
0.1	1.1		
0.01	0.51		
0.001	0.23		

CALCULATED CARBON REQUIREMENTS TO ACHIEVE INDICATED CHANGE IN CONCENTRATION (a)

SINGLE STAGE POWDERED CARBON

C_f, mg/l

C_o, mg/l	0.1	0.01	0.001
1.0	800	1,900	4,300
0.1		180	430
0.01			39

GRANULAR CARBON COLUMN

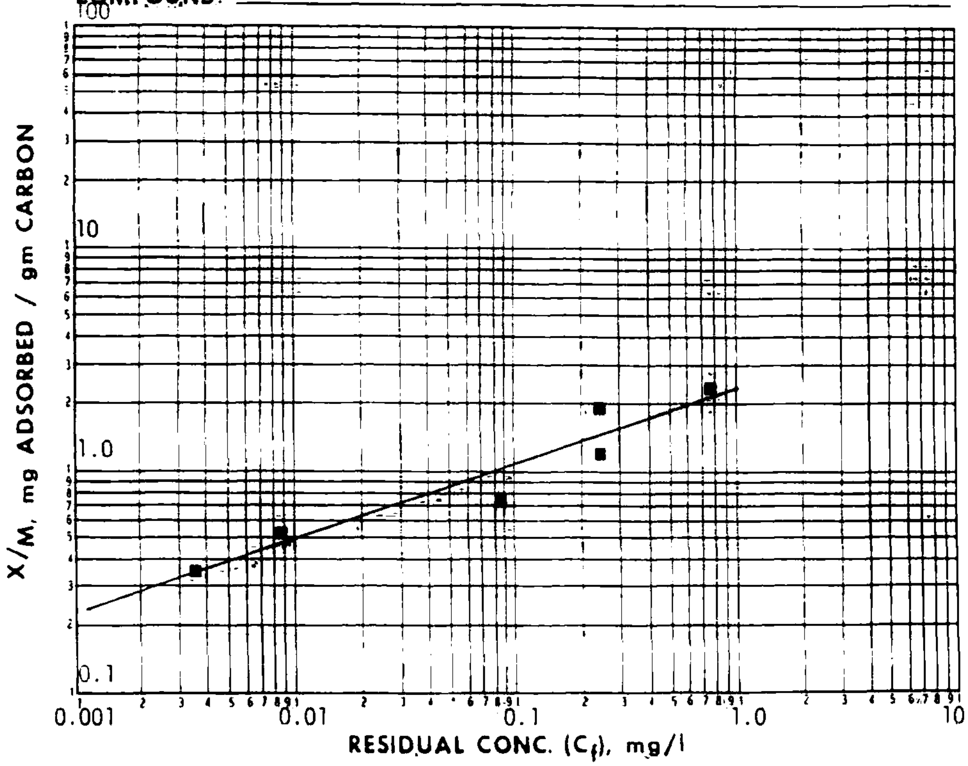
C_o, mg/l	
1.0	400
0.1	90
0.01	20

(a) Carbon doses in mg/l at neutral pH.

ANALYTICAL METHOD: G. C. - Purge and Trap

REMARKS:

COMPOUND: 1,1,1-Trichloroethane



	■ pH= 5.3			pH=			pH=		
CARBON DOSE mg/l	C_f	$C_o-C_f=X$	X/M	C_f	$C_o-C_f=X$	X/M	C_f	$C_o-C_f=X$	X/M
0	1.000								
96	0.768	0.232	2.41						
385	0.240	0.760	1.97						
577	0.238	0.762	1.32						
1154	0.084	0.916	0.794						
1923	0.0087	0.991	0.516						
2692	0.0035	0.9965	0.370						

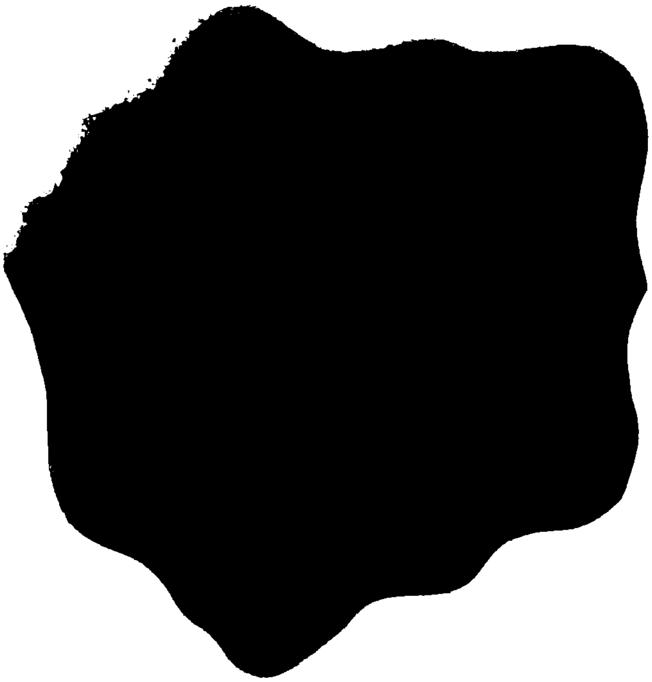
United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/8-80-023
April 1980

Research and Development

Carbon Adsorption Isotherms for Toxic Organics



Groundwater Monitoring and Remediation Techniques Short Course

Activated Carbon

To estimate the capacity of carbon, use the x/M value that corresponds to the influent concentration, C_o. This value, x/M @ C_o, represents the maximum amount of contaminant adsorbed per unit weight of carbon when the carbon is in equilibrium with the untreated concentration.

For complete removal of the contaminant

$$Y = C_o / (x/M \ @ \ C_o)$$

Where

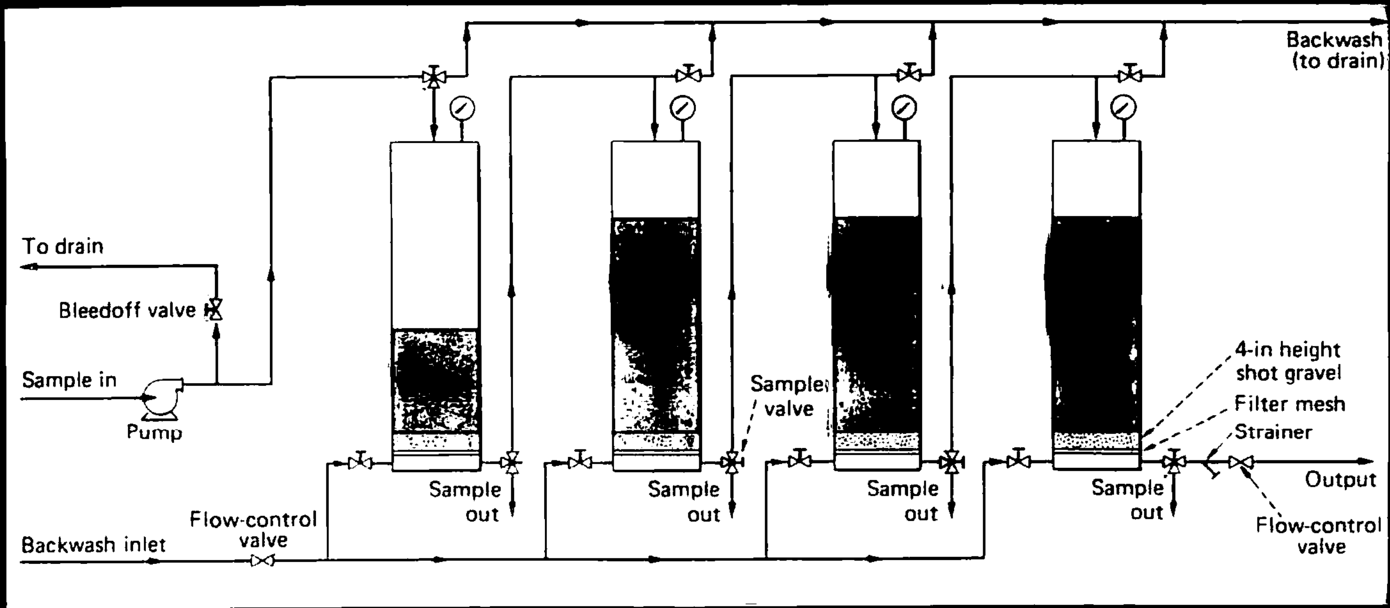
Y = weight of carbon required per unit volume of contaminated liquid

Activated Carbon

Dynamic Column Study

- Determines Optimum Operating Capacity
- Determines Contact Time
- Necessary for Adsorber Size and System Configuration

Superficial contact time ranges between 15 to 60 minutes per column. The rate of flow per unit area of column, surface loading, is in the range of 2 GPM/ft^2

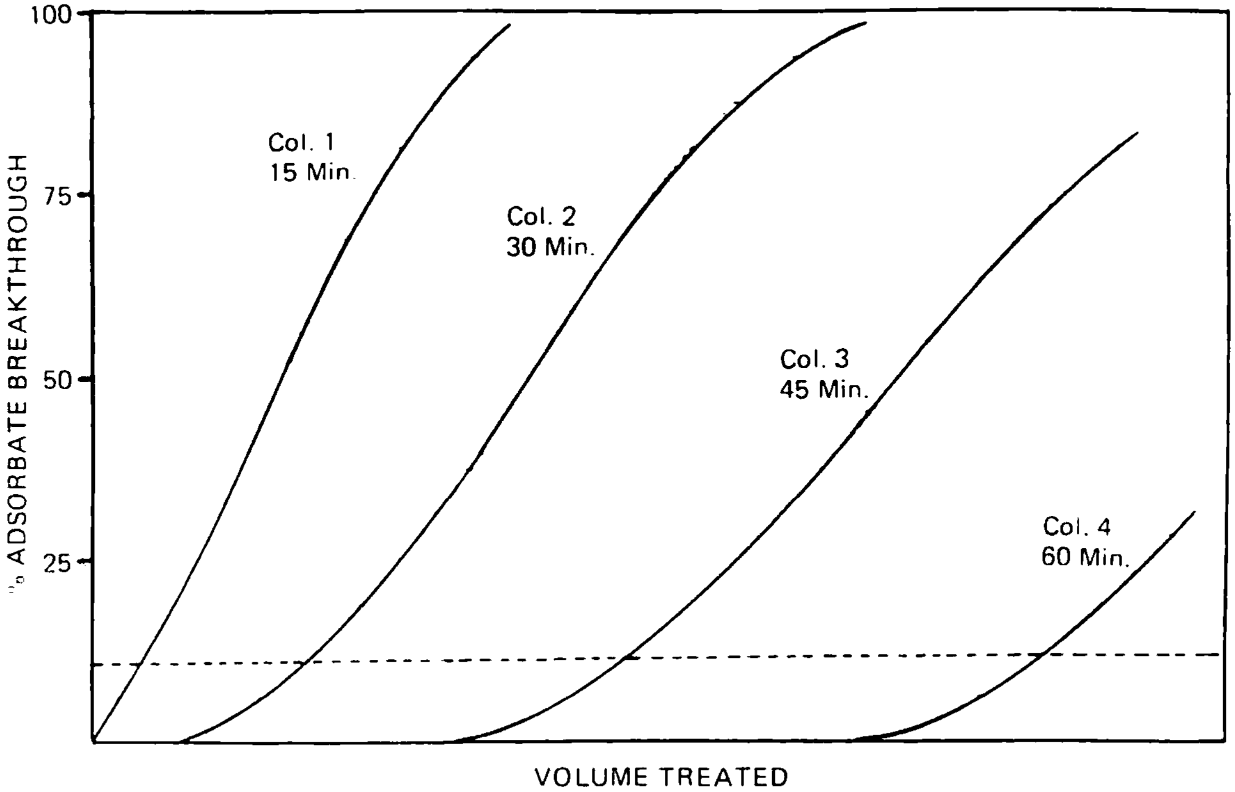


Laboratory series column adsorption test.

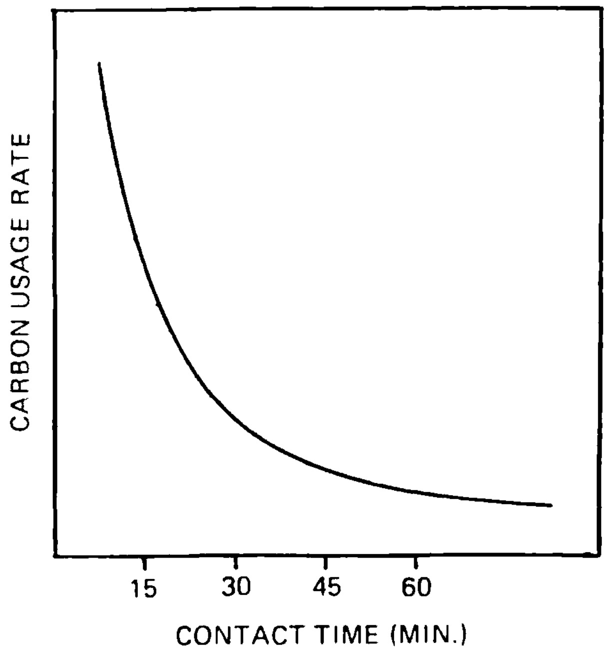
Activated Carbon

Dynamic Column Study

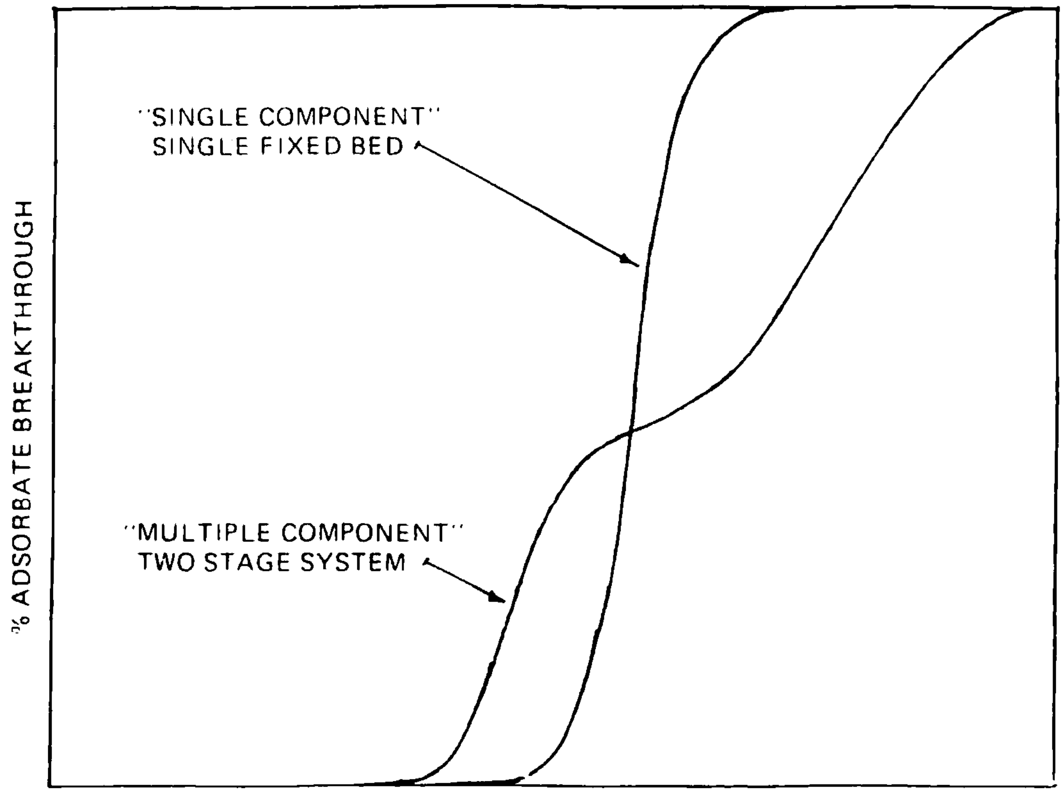
- Pump water through columns
- Take samples of effluent from each column
- Obtain a series of curves, each representing a column. The curves represent the concentration or amount of contaminants present in the effluent which have passed through the column unadsorbed.



Column study results: breakthrough curves.



Optimum carbon contact time.



Mass transfer zones for two typical breakthrough curves.

ACTIVATED CARBON

CLASSES OF ORGANICS COMMONLY REMOVED

In general compounds which are non-polar and of high molecular weight (in the broad range of from four to 20 carbon atoms) are readily removed from wastewater by the activated carbon.

Following classes are commonly adsorbed by carbon:

- o Aromatic Hydrocarbons (benzene, toluene, xylene)
- o Polynuclear Aromatic (napthalene, anthracene, biphenyls)
- o Chlorinated Aromatics (chlorobenzene, polychlorinated biphenyls, aldrin, endrin, toxaphene, DDT)
- o Phenolics (phenol, cresol, resorcinol and polyphenyls such as tannin and lignin derivatives)
- o Chlorinated Phenolics (trichlorophenol, pentachlorophenol)
- o High Molecular Weight Aliphatic and Branch Chain Hydrocarbons (gasolene, kerosene)
- o Chlorinated Aliphatic Hydrocarbons (carbon tetrachloride, perchloroethylene)
- o High Molecular Weight Aliphatic Acids and Aromatic Acids (tar acids, 2,4-dichlorobenzoic acid, sulfonated lignins, benzoic acid)
- o High Molecular Weight Aliphatic Amines and Aromatic Amines (aniline, toluene diamine)
- o High Molecular Weight Ketones, Esters, Ethers and Alcohols (hydroquinone, polyethlene glycol)
- o Surfactants (alkyl benzene sulfonates, linear alcohol sulfates)
- o Soluble Organic Dyes (methylene blue, Indigo carmine, Benzopurpurin 4B Phthalocyanines)

Source Calgon Bulletin

AMENABILITY OF TYPICAL ORGANIC COMPOUNDS TO ACTIVATED CARBON ADSORPTION

Compound	Molecular weight	Aqueous solubility (%)	Concentration (mg/l)		Adsorbability*	
			Initial (C_o)	Final (C_f)	g compound/ g carbon	Percent reduction
Alcohols						
Methanol	32.0	∞	1,000	964	0.007	3.6
Ethanol	46.1	∞	1,000	901	0.020	10.0
Propanol	60.1	∞	1,000	811	0.038	18.9
Butanol	74.1	7.7	1,000	466	0.107	53.4
n-Amyl alcohol	88.2	1.7	1,000	282	0.155	71.8
n-Hexanol	102.2	0.58	1,000	45	0.191	95.5
Isopropanol	60.1	∞	1,000	874	0.025	12.6
Allyl alcohol	58.1	∞	1,010	789	0.024	21.9
Isobutanol	74.1	8.5	1,000	581	0.084	41.9
t-Butanol	74.1	∞	1,000	705	0.059	29.5
2-Ethyl butanol	102.2	0.43	1,000	145	0.170	85.5
2-Ethyl hexanol	130.2	0.07	700	10	0.138	98.5
Aldehydes						
Formaldehyde	30.0	∞	1,000	908	0.018	9.2
Acetaldehyde	44.1	∞	1,000	881	0.022	11.9
Propionaldehyde	58.1	22	1,000	723	0.057	27.7
Butyraldehyde	72.1	7.1	1,000	472	0.106	52.8
Acrolein	56.1	20.6	1,000	694	0.061	30.6
Crotonaldehyde	70.1	15.5	1,000	544	0.092	45.6
Benzaldehyde	106.1	0.33	1,000	60	0.188	94.0
Paraldehyde	132.2	10.5	1,000	261	0.148	73.9
Amines						
Di-N-Propylamine	101.2	∞	1,000	198	0.174	80.2
Butylamine	73.1	∞	1,000	480	0.103	52.0
Di-N-Butylamine	129.3	∞	1,000	130	0.174	87.0
Allylamine	57.1	∞	1,000	686	0.063	31.4
Ethylenediamine	60.1	∞	1,000	893	0.021	10.7

AMENABILITY OF TYPICAL ORGANIC COMPOUNDS TO ACTIVATED CARBON ADSORPTION

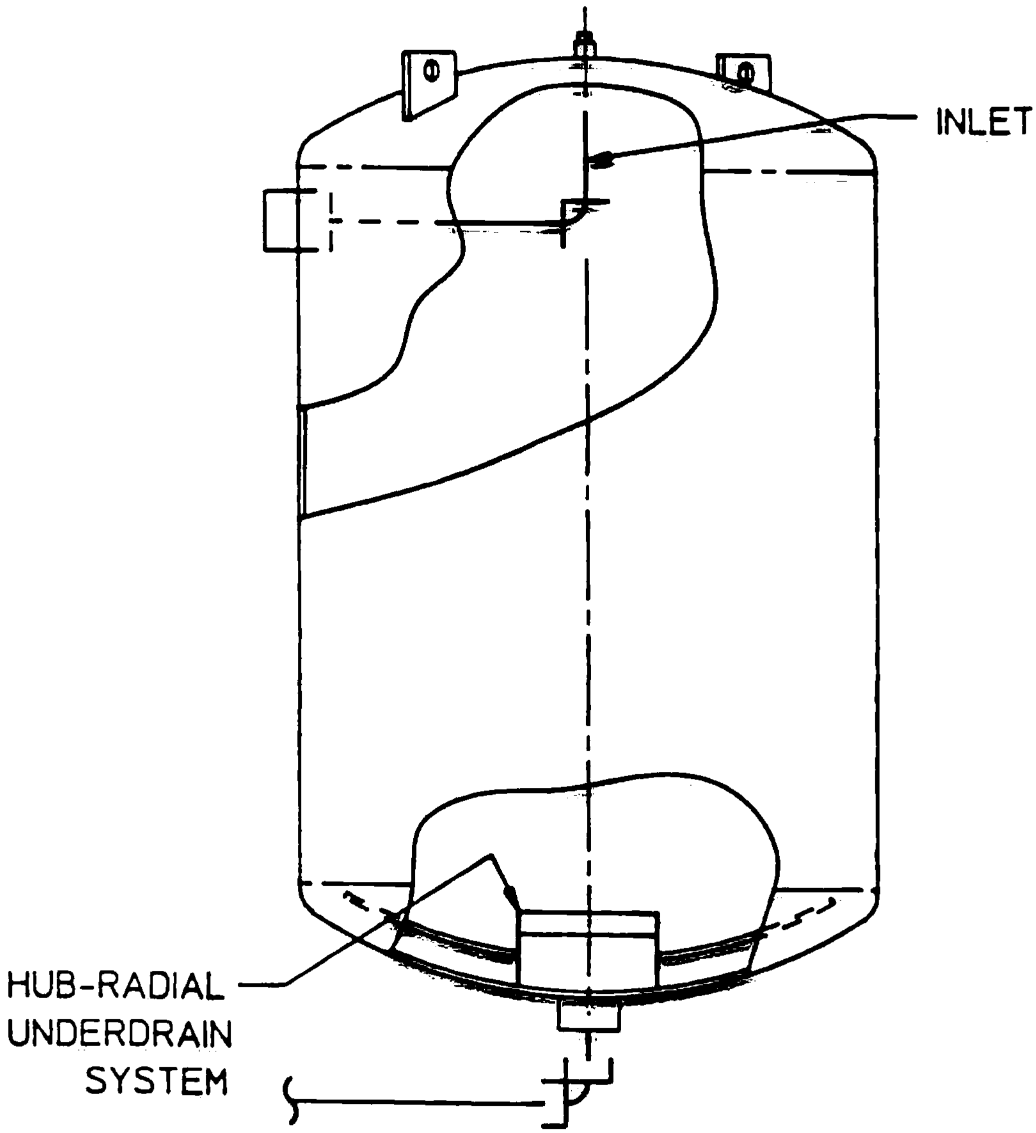
Compound	Molecular weight	Aqueous solubility (%)	Concentration (mg/l) Initial (C_o)	Concentration (mg/l) Final (C_f)	Adsorbability* g compound/ g carbon	Adsorbability* Percent reduction
Diethylenetriamine	103.2	∞	1,000	706	0.062	29.4
Monoethanolamine	61.1	∞	1,012	939	0.015	7.2
Diethanolamine	105.1	95.4	996	722	0.057	27.5
Triethanolamine	149.1	∞	1,000	670	0.067	33.0
Monoisopropanolamine	75.1	∞	1,000	800	0.040	20.0
Diisopropanolamine	133.2	87	1,000	543	0.091	45.7
Pyridines and morpholines						
Pyridine	79.1	∞	1,000	527	0.095	47.3
2 Methyl 5 Ethyl pyridine	121.2	sl. sol.	1,000	107	0.179	89.3
N Methyl morpholine	101.2	∞	1,000	575	0.085	42.5
N Ethyl morpholine	115.2	∞	1,000	467	0.107	53.3
Aromatics						
Benzene	78.1	0.07	416	21	0.080	95.0
Toluene	92.1	0.047	317	66	0.050	79.2
Ethyl benzene	106.2	0.02	115	18	0.019	84.3
Phenol	94	6.7	1,000	194	0.161	80.6
Hydroquinone	110.1	6.0	1,000	167	0.167	81.3
Aniline	93.1	3.4	1,000	251	0.150	74.9
Styrene	104.2	0.03	180	18	0.028	88.8
Nitrobenzene	123.1	0.19	1,023	44	0.196	95.6
Esters						
Methyl acetate	74.1	31.9	1,030	760	0.054	26.2
Ethyl acetate	88.1	8.7	1,000	495	0.100	50.5
Propyl acetate	102.1	2	1,000	248	0.149	75.2
Butyl acetate	116.2	0.68	1,000	154	0.169	84.6
Primary amyl acetate	130.2	0.2	985	119	0.175	88.0
Isopropyl acetate	102.1	2.9	1,000	319	0.137	68.1

AMENABILITY OF TYPICAL ORGANIC COMPOUNDS TO ACTIVATED CARBON ADSORPTION

Compound	Molecular weight	Aqueous solubility (%)	Concentration (mg/l)		Adsorbability*	
			Initial (C_o)	Final (C_f)	g compound/ g carbon	Percent reduction
Methyl propyl ketone	86.1	4.3	1,000	305	0.139	69.5
Methyl butyl ketone	100.2	v. sl. sol.	988	191	0.159	80.7
Methyl isobutyl ketone	100.2	1.9	1,000	152	0.169	84.8
Methyl isoamyl ketone	114.2	0.54	986	146	0.169	85.2
Diisobutyl ketone	142.2	0.05	300	nil	0.060	100.0
Cyclohexanone	98.2	2.5	1,000	332	0.134	66.8
Acetophenone	120.1	0.55	1,000	28	0.194	97.2
Isophorone	138.2	1.2	1,000	34	0.193	96.6
Organic Acids						
Formic acid	46.0	∞	1,000	765	0.047	23.5
Acetic acid	60.1	∞	1,000	760	0.048	24.0
Propionic acid	74.1	∞	1,000	674	0.065	32.6
Butyric acid	88.1	∞	1,000	405	0.119	59.5
Valeric acid	102.1	2.4	1,000	203	0.159	79.7
Caproic acid	116.2	1.1	1,000	30	0.194	97.0
Acrylic acid	72.1	∞	1,000	355	0.129	64.5
Benzoic acid	122.1	0.29	1,000	89	0.183	91.1
Oxides						
Propylene oxide	58.1	40.5	1,000	739	0.052	26.1
Styrene oxide	120.2	0.3	1,000	47	0.190	95.3

* Dosage — 5 g Carbon C/l solution.

ACTIVATED CARBON FILTER



Enhanced Oxidation

- Technology Uses "Supercharged" Oxidation to Destroy Organic Compounds into CO_2, Water, Chlorides, and Smaller Organic Compounds (Where Incomplete Oxidation Occurs.)

- Chemical Oxidants, Such as Hydrogen Peroxide and/or Ozone, are Added to Groundwater in the Presence of UV Light to Create Free Radicals. The Free Radicals Greatly Enhance the Oxidation Rate of the Organic Compounds in the Groundwater. Advanced "Catalysts" May Be Added to Speed Reaction Rates of Refractive Compounds Such as Carbon Tetrachloride, Chloroform, And Trichloroethane.

REACTION RATES OF OZONE AND HYDROXYL RADICALS WITH VARIOUS CLASSES OF ORGANIC COMPOUNDS

COMPOUND	k, in L $mole^{-1}$ s^{-1}	
	O_3	OH
Olefins	1 to 450 x 10^3	10^9 to 10^{11}
S-containing organics	10 to 1.6 x 10^3	10^9 to 10^{10}
Phenols	10^3	10^9
N-containing organics	10 to 10^2	10^8 to 10^{10}
Aromatics	1 to 10^2	10^8 to 10^{10}
Acetylenes	50	10^8 to 10^9
Aldehyde	10	10^9
Ketones	1	10^9 to 10^{10}
Alcohols	10^{-2} to 1	10^8 to 10^9
Alkanes	10^{-2}	10^6 to 10^9
Carboxylic acids	10^{-3} to 10^{-2}	10^7 to 10^9

Enhanced Oxidation

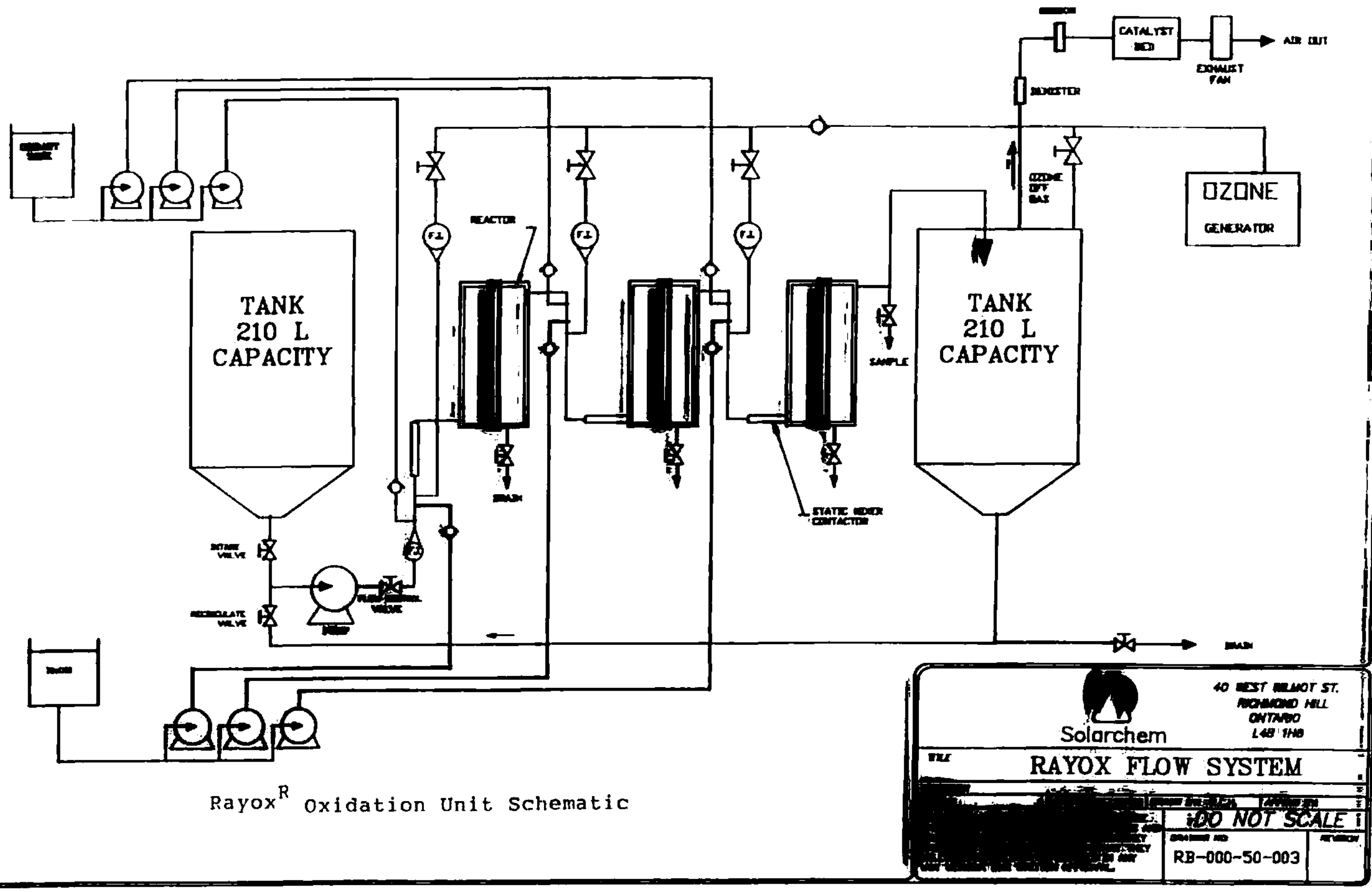
Successfully Destroyed Contaminants:

Propellants	Freon	TPH
Complexed Cyanides	BETXs	Dioxins,
Furans	MTBE	Pesticides
DDT	2,4D	Ethanol
Dinoseb	Roundup	Methanol
PAHs	Mercaptans	Hydrazines
Solvents	PCP	Chlorinated Solvents
H_2S	Ordnance Compounds:	Color Organic Dyes
TNT	Phenols	- DNT
PCBs	- NG	Glycol
- TMETN	Ketones	Alehydes
- TEGDN	Citric Acid	- PGDN

Enhanced Oxidation

Typical Treatment Systems Include:

- Annular Reactor(s) in Series
- High Intensity UV Lamp(s) at Center of Reactor
- Quartz Sleeves Surrounding Lamp(s)
- Stainless Steel Construction
- Chemical Addition Systems
- O_3 Venting System
- Tankage



Rayox[R] Oxidation Unit Schematic

Enhanced Oxidation

Advantages:

- No Toxics are Emitted to Air
- No Toxics are Adsorbed onto Media Requiring Landfilling or Regeneration
- Does Not Merely Concentrate Contaminants
- Effective for Wider Range of Contaminants Than Biotreatment
- Can Be Run Intermittently

Enhanced Oxidation

Site 1

Treatment Time (Minutes) Chemical (ppb)

02.55 PCE704 ND ND

1,1 - DCE 263 ND ND

Freon - TF717553

TCE 54 ND ND

1,1,1 - TCA-2920

UV Dose:	160 Watt/l
H_2O_2 Dose:	7 mg/l/min
Oxidation Time:	2.5 minutes
Flow Rate:	400 GPM
Cost/1000 gallons:	$1.37

Enhanced Oxidation

Site 2

Treatment Time (Minutes) Chemical (ppb)

024	TCE	1924	57	ND
trans 1,2 -DCE	198	ND	ND	

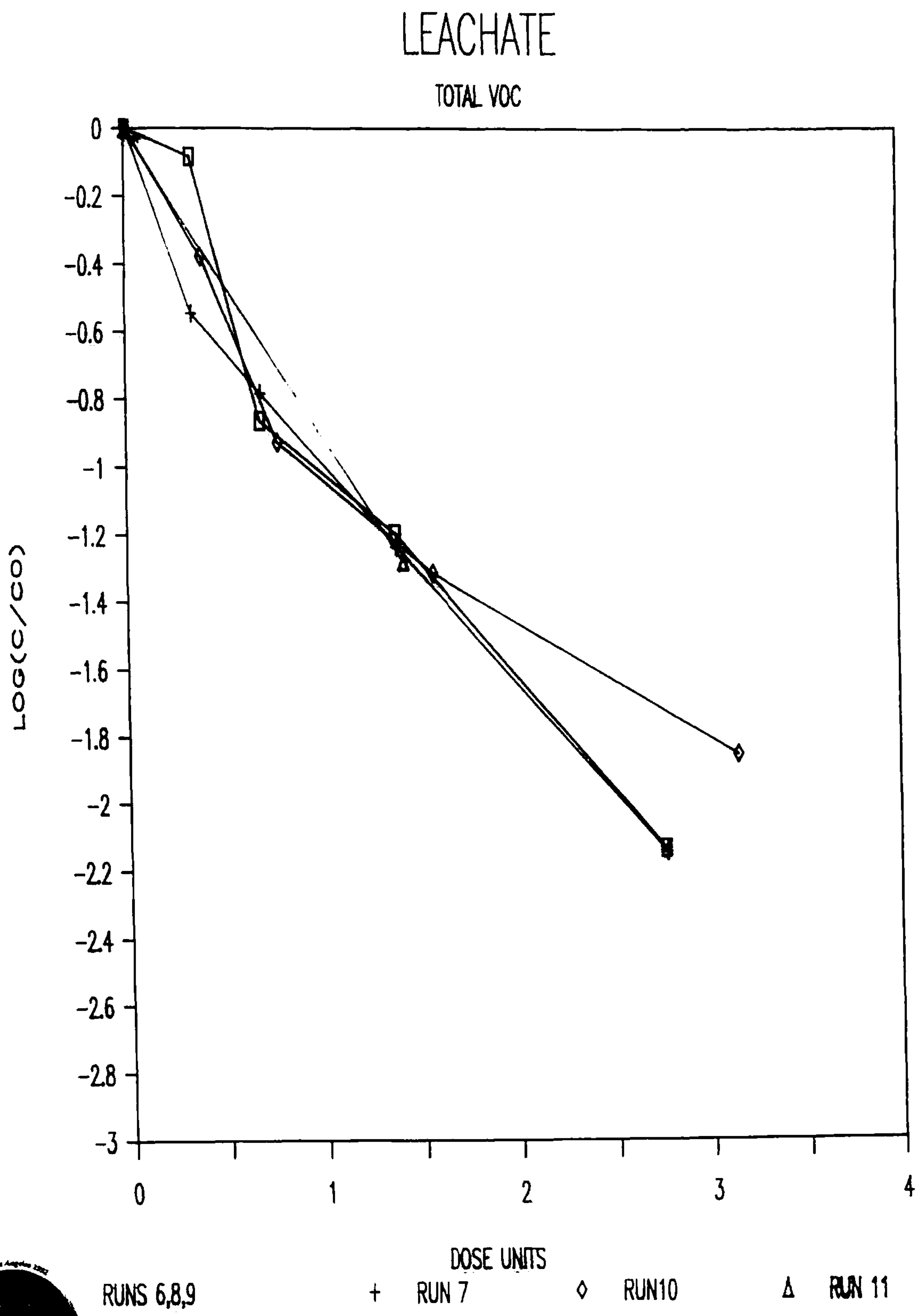
UV Dose:	160 Watt/l
H_2O_2 Dose:	10 mg/l/min
Oxidation Time:	4 minutes
Flow Rate:	40 GPM
Cost/1000 gallons:	$2.08

Enhanced Oxidation

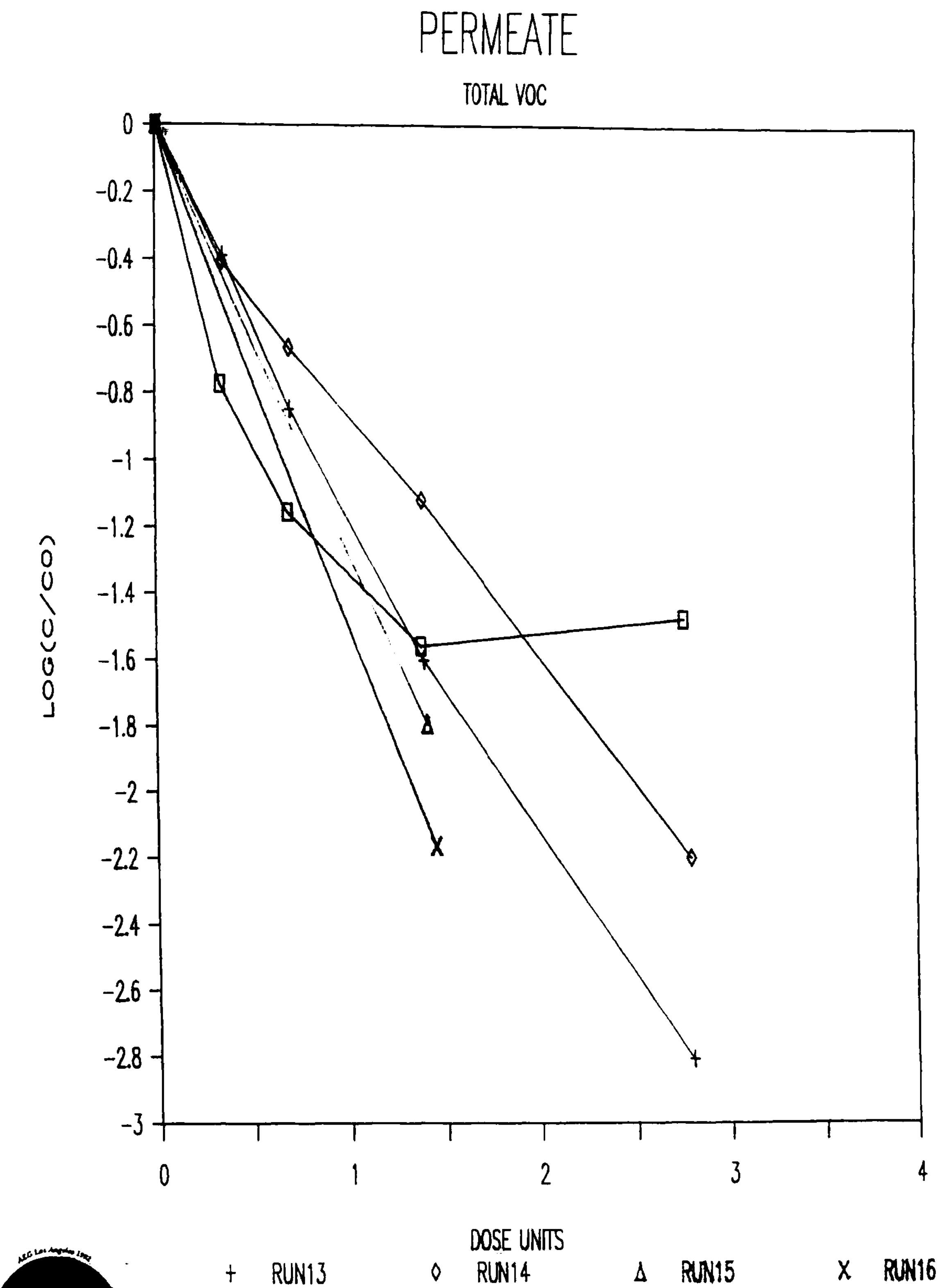
Site 3

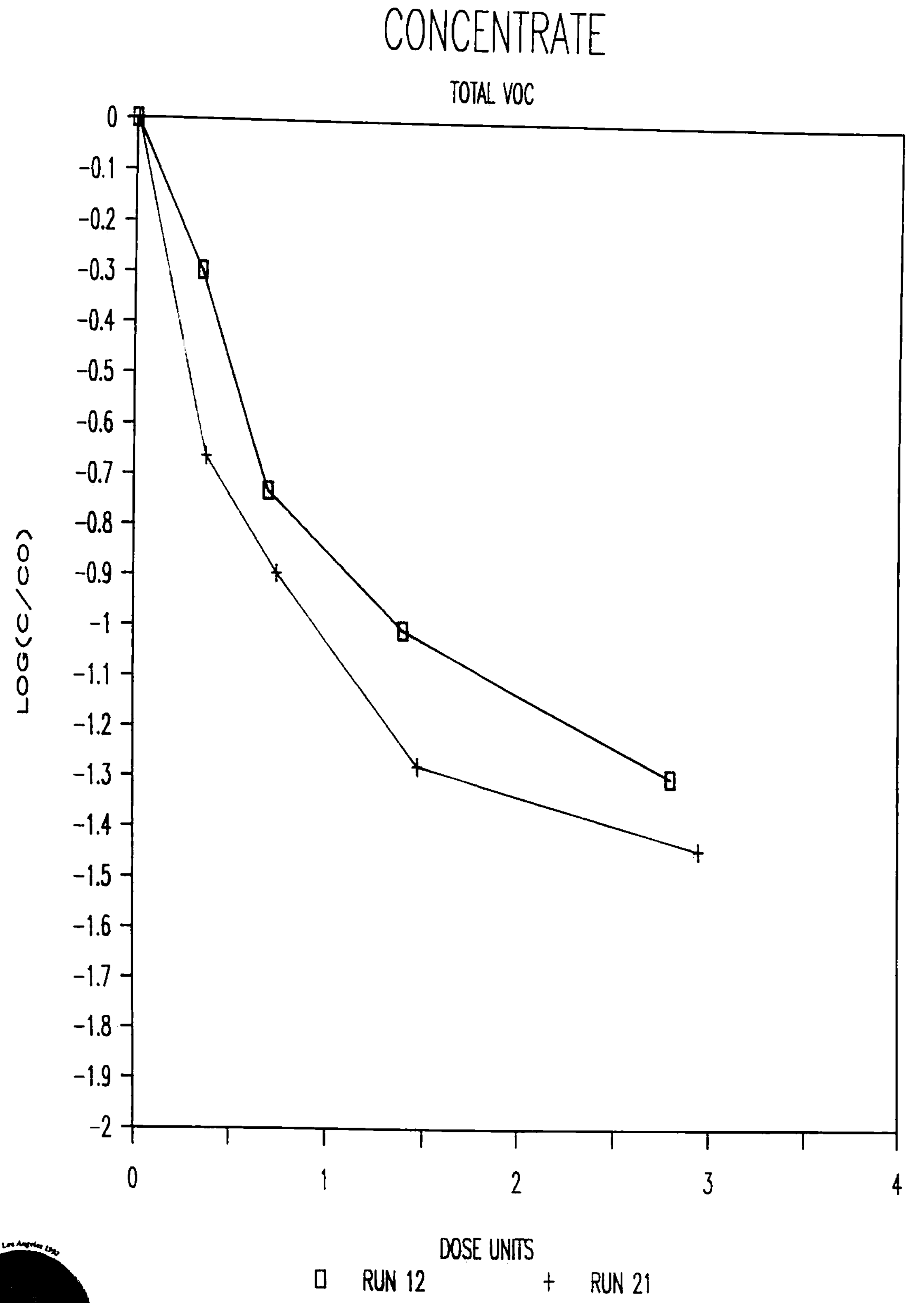
Treatment Time (Minutes) Chemical (ppb)
01545 Chloroform 7900 2300 38
1,2 - DCA 16900110ND Meth Chloride 3000
230 ND Carbon Tet-45 ND 1,1,1 - TCA -56
ND

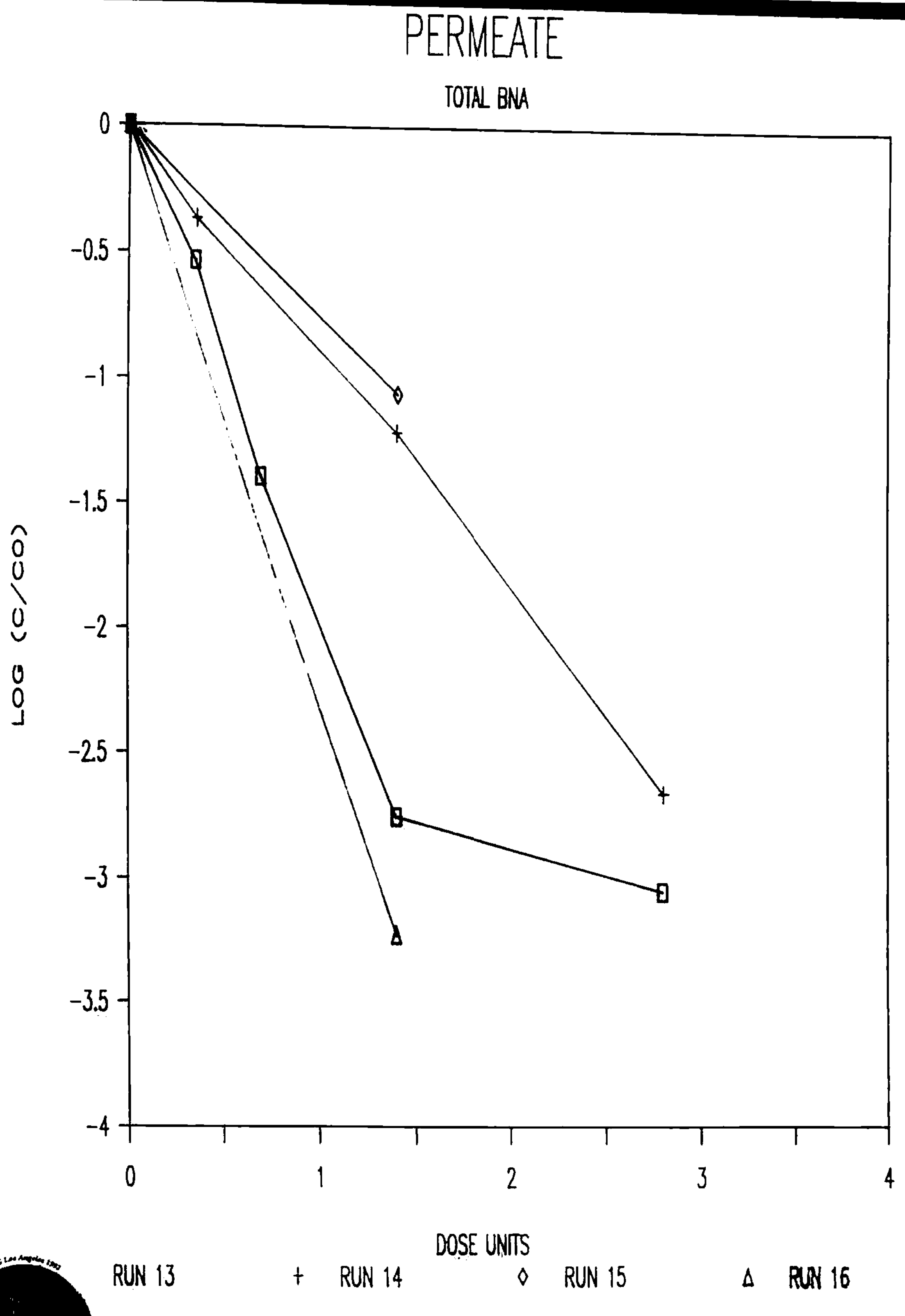
UV Dose: 160 Watt/l
H_2O_2 Dose: 150 mg/l/min
Oxidation Time: 45 minutes
Flow Rate: 15 GPM
Cost/1000 gallons: $15.20

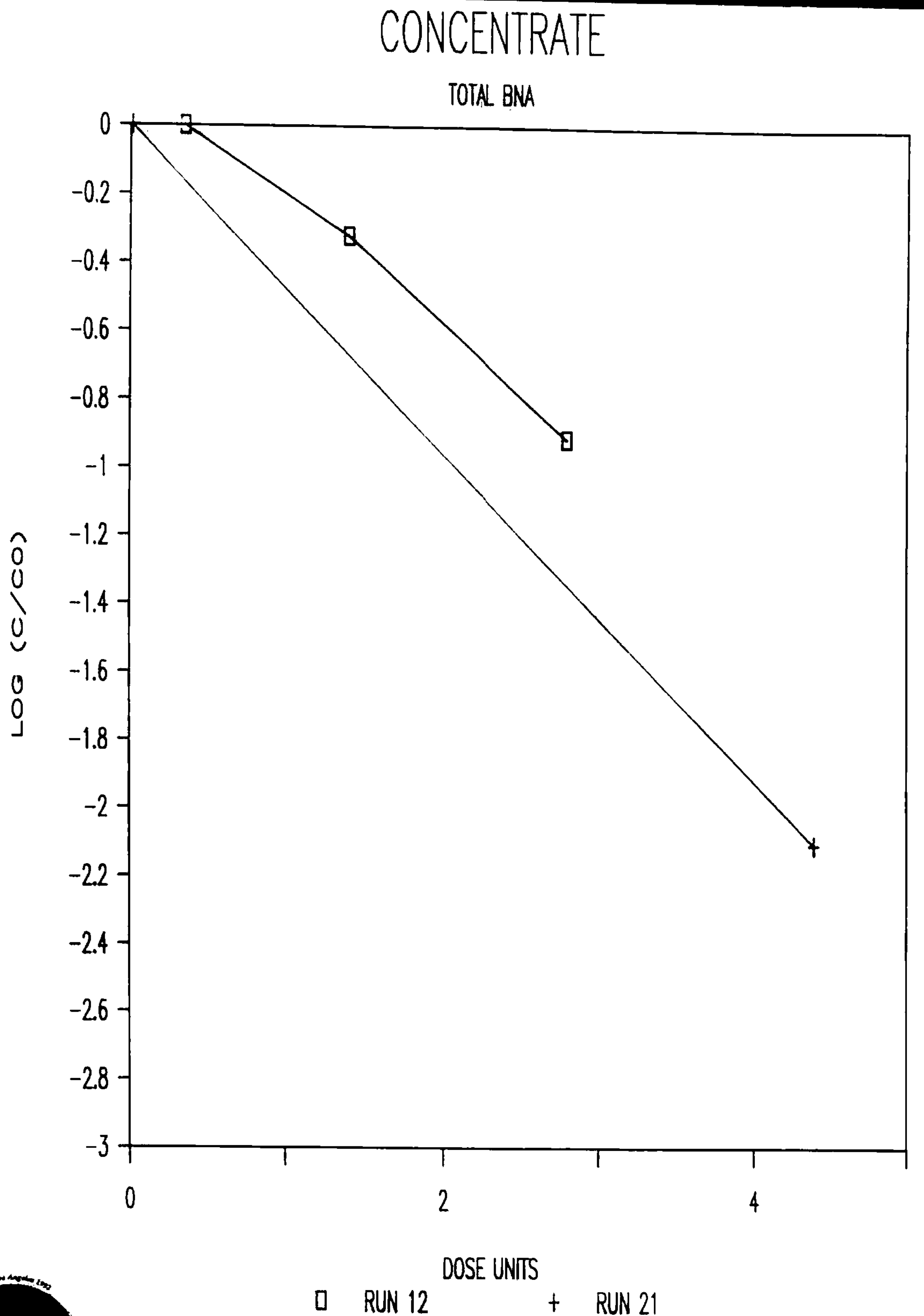


LEACHATE
TOTAL VOC
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
-2.8
-3
LOG(C/CO)
0
1
2
3
4
DOSE UNITS
RUNS 6,8,9
+ RUN 7
◊ RUN10
Δ RUN 11


PERMEATE
TOTAL VOC
LOG(C/CO)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
-2.8
-3
0
1
2
3
4
DOSE UNITS
+ RUN13
◊ RUN14
Δ RUN15
X RUN16


CONCENTRATE
TOTAL VOC
LOG(C/CO)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
0
1
2
3
4
DOSE UNITS
RUN 12
RUN 21


PERMEATE
TOTAL BNA
LOG (C/CO)
DOSE UNITS
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0
1
2
3
4
RUN 13
+ RUN 14
◊ RUN 15
Δ RUN 16


CONCENTRATE
TOTAL BNA
LOG (C/CO)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
-2.8
-3
0
2
4
DOSE UNITS
RUN 12
RUN 21

Enhanced Reduction

Works on the Premise That Difficult to Oxidize Substances May Be Easy to Reduce.

Technology Uses the Hydrated Electron as a Reducing Agent to Photodegrade Refractory Substances, Such As Chloroalkanes, Aliphatic Keytones, and Some Nitro Compounds.

The Reaction Rate Constants of Hydrated Electrons are Higher Than the Rate Constants of the Free Radicals with Chloroalkanes. The Difference Increases with Increasing Number of Chlorine Atoms.

The Technology Can Be Combined With and Can Follow Enhanced Oxidation.

Comparison of rate constants for the hydroxyl radical and the hydrated electron with chloro-organic compounds

Pollutant	Rate Constant / $10^9 M^{-1}s^{-1}$ hydrated electron	hydroxyl radical
CH_2Cl_2	6.3	0.058
$CHCl_3$	30	~0.005
CCl_4	16	~0.001
$CH_2=CCl_2$	23	6.8
$CHCl=CCl_2$	19	4.2

Enhanced Reduction

Photodegradation Usually Follows First-Order Kinetics

$$EE/O = \frac{3785\,P\,(t/60)}{V\,\log\,(c_i/c_f)}$$

EE/O = Electrical energy per order or the electrical energy (kWh) to reduce the concentration of a pollutant by one order of magnitude in 1000 gallons (3785 liters)

P = lamp power in (kW)

t = Irradiation time (minutes)

V = Reactor volume (liters)

c_i = Initial concentration

c_f = Final concentration

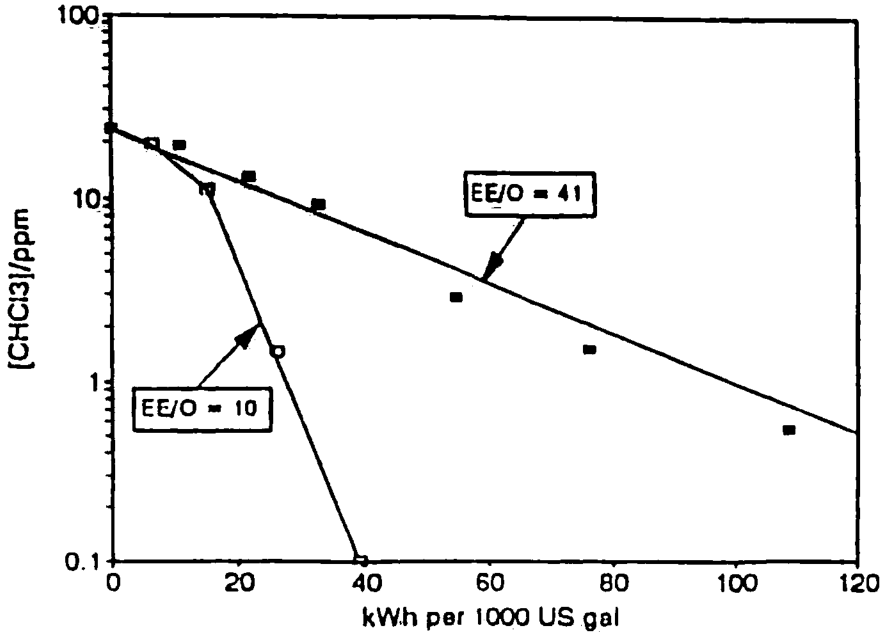
Enhanced Reduction

EE/O is Related to the First-Order Rate Constant, k (min $^{-1}$), by:

$$k = \frac{145.25\ P}{V\ (EE/O)}$$

EE/O Values < 10 Are Very Good.

COMPARISON OF Rayox® AND Rayox® R TREATMENT OF $CHCl_3$



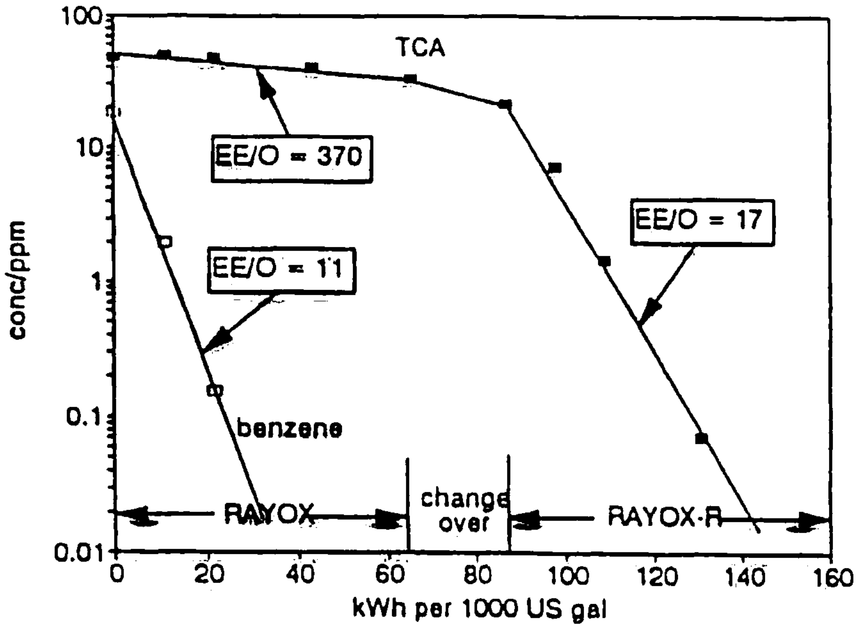


Figure 3 shows an example where a mixture of benzene (20 ppm) and trichloroethane (TCA) is subjected to a sequential Rayox® /Rayox® R treatment. In the Rayox® phase (0- 65 kWh per 1000 USgal), the benzene treats very well (EE/O = 11), while the TCA is hardly treated at all (EE/O = 370). However, after the switch-over to the Rayox® R process, the TCA treats very well (EE/O = 17).