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March 3, 1849

Techniques of Water-Resource Investigations of the United States Geological Survey

Chapter F1

APPLICATION OF DRILLING, CORING, AND SAMPLING TECHNIQUES TO TEST HOLES AND WELLS

By Eugene Shuter and
Warren E. Teasdale

Book 2

COLLECTION OF ENVIRONMENTAL DATA

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1989

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called "Books" and further subdivided into sections and chapters. Section F of Book 2 is on drilling and sampling methods.

The unit of publication, the chapter, is limited to a narrow field of subject matters. This format permits flexibility in revision and publication as the need arises. "Application of drilling, coring, and sampling techniques to test holes and wells" is the first chapter to be published under Section F of Book 2.

TECHNIQUES OF WATER-RESOURCES INVESTIGATIONS OF THE U.S. GEOLOGICAL SURVEY

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TWRI 3-B4.	Regression modeling of ground-water flow, by R.L. Cooley and R.L. Naff. [in press].

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[1] Spanish translation also available.

TWRI 3-B5. Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems—An introduction, by O.L. Franke, T.E. Reilly, and G.D. Bennett. 1987. 15 pages.

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Conversion factors

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meters (m)
gallon per minute (gal/min)	0.063081	liters per second (L/s)
inch (in.)	25.40	millimeters (mm)
pound, avoirdupois (lb)	453.6	grams (g)
quart (qt)	0.9464	liters (L)
pound per square inch ($lb/in.^2$)	6.895	kilopascals (kPa)

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:
°F = 1.8° + 32.

APPLICATION OF DRILLING, CORING, AND SAMPLING TECHNIQUES TO TEST HOLES AND WELLS

By Eugene Shuter and Warren E. Teasdale

Abstract

The purpose of this manual is to provide ground-water hydrologists with a working knowledge of the techniques of test drilling, auger drilling, coring and sampling, and the related drilling and sampling equipment. For the most part, the techniques discussed deal with drilling, sampling, and completion of test holes in unconsolidated sediments because a hydrologist is interested primarily in shallow-aquifer data in this type of lithology. Successful drilling and coring of these materials usually is difficult, and published research information on the subject is not readily available. The authors emphasize in-situ sampling of unconsolidated sediments to obtain virtually undisturbed samples.

Particular attention is given to auger drilling and hydraulic-rotary methods of drilling because these are the principal means of test drilling performed by the U.S. Geological Survey during hydrologic studies. Techniques for sampling areas contaminated by solid or liquid waste are discussed. Basic concepts of well development and a detailed discussion of drilling muds, as related to hole conditioning, also are included in the report. The information contained in this manual is intended to help ground-water hydrologists obtain useful subsurface data and samples from their drilling programs.

INTRODUCTION

Background

Although published data are available concerning drilling and coring of wells and test holes, these data generally are incomplete in respect to the drilling performed by ground-water hydrologists and other Earth scientists. Much of the available data is a result of practical knowledge gained from the drilling of hundreds of thousands of wells for the production of oil, gas, water, and minerals. In addition to this practical knowledge, a considerable body of research relates to drillability of rock, various types of drilling rigs, and associated equipment and drilling fluids. Although this available information is vast and its quality, for the most part, is excellent, usually it does not meet particular needs of a ground-water hydrologist because a hydrologist usually in interested in very detailed information about shallow aquifers in unconsolidated materials. Unfortunately, these types of materials are the most difficult in which to core and complete representative test holes, and these materials have been the least studied and have little published data about them.

Purpose and Scope

The purpose of this manual is to describe practical aspects of drilling, coring, and sampling techniques to assist personnel concerned with collecting useful subsurface geohydrologic data, through the use of in-house drilling equipment or contract drilling. Particular emphasis is placed on techniques to obtain representative or undisturbed core samples of unconsolidated materials. Emphasis also is placed on techniques and ideas for smpling in areas where contamination by solid or liquid waste likely would be encountered. Although almost all practical drilling methods are discussed, auger drilling and hydraulic-rotary methods are emphasized because these two methods represent more than 90 percent of the drilling performed by the U.S. Geological Survey during hydrologic investigations. The U.S. Geological Survey uses those methods for installation of most test holes and observation wells. Some basic approaches to well development and detailed section on the practical aspects of drill muds and their relationship to hole conditioning also are included. A basic understanding of drilling equipment and terminology is assumed.

Acknowledgments

The authors are grateful to Mr. Arnold I. Johnson, who established the first hydrologic laboratory in the Water Resources Division 30 years ago. The laboratory performed the first in-house service drilling and sampling in the Division. The present research-drilling project evolved as a result of these earlier efforts and the greater needs for complex geohydrologic data of the U.S. Geological Survey. We wish to thank Mr. Robert R. Pemberton, U.S. Geological Survey, whose field-drilling and sampling expertise provided much of the field data and techniques explained in this report. Special acknowledgment also is given to Mr. Tom Kostick of the U.S. Geological Survey for his expert rendering of the technical illustrations by airbrush technique.

TECHNIQUES FOR DRILLING, INSTALLING, AND COMPLETING WELLS

Auger Drilling

Auger drilling is a very valuable technique for the collection of subsurface information; however, it is restricted to the drilling of unconsolidated materials or softer rocks, and it has limitations based on types of materials drilled, size of rig, diameter of augers, and expertise of the operator. Auger drilling offer means of coring, sampling, installation of observation wells and neutron moisture-meter access tubes, and other types of point-sampling devices. Hollow-stem auger drilling, particularly, offers one of the best methods available for collecting uncontaminated samples representative of shallow, unconsolidated formations. The method is unsurpassed for collecting core samples in a contaminated environment, such as around solid- or liquid-chemical-waste pits, sanitary land fills, and radioactive-waste storage areas.

Many think that, if a saturated zone is encountered in the upper part of a hollow-stem auger-drilled and sampled hole, this water will move down the auger and contaminate any samples collected in the lower part of the hole. This is not true if the cuttings are left on the auger flights using slow rotation so cuttings will not move up the hole. This mixture of cuttings has very low vertical permeability preventing downward movement of the water (table 1). In this example, a perched-water table was encountered at 29 ft and partially saturated material was encountered to 44 ft at which depth another perched zone was encountered. However, the samples collected below 45 ft were not wetted from the above perched zones.

Auger drilling is one of the best methods for collecting uncontaminated, representative samples of shallow, unconsolidated formations, particularly the hollow-stem method. We highly favor this method for sampling contaminated-environment lithologies. Auger drilling probably is the most rapid and economical method of drilling in unconsolidated sediments to relatively shallow depths. Soil profiles can be determined, and disturbed soil samples of penetrated materials can be collected from sample returns of augered materials. However, auger drilling is limited to drilling unconsolidated materials or softer rock. In materials where the auger hole remains open without caving, the hole easily can be cased after removal of the auger. Auger drilling usually is done without using air, water, or any other media to flush the hole. Cuttings are moved out of the hole and to the surface by the augering action.

Two basic types of continuous-flight augers are used for drilling: the solid-stem type and the hollow-stem type. Solid-stem augers usually are used for general reconnaissance-exploration drilling because they are more convenient to use, less complex, faster, and easier to handle than larger hollow-stem augers. Hollow-stem augers generally are used for more extensive testing and more detailed soil-sampling projects. They are used to drill and case the hole simultaneously, thereby eliminating hole-caving problems and contamination of soil samples. Also, well casing, aquifer-testing equipment, logging probes, and water- or soil-sampling apparatus can be installed directly through hollow-stemaugers.

Table 1.—Data and sample analyses from a hole drilled using a hollow-stem auger

[ft, feet; µmho/cm, micromhos per centimeter at 25°C; mm, millimeter]

Depth (ft)	NO_3—N[1]	pH	Specific conductance, µmho/cm	Soil moisture (percent by volume)	Porosity (percent)	Median grain size (mm)
0	---	8.13	127			
1	---	8.29	38			
3.5	1.1	8.70	87	3.17	47.1	0.10
4.5	1.9	8.70	95	3.53	---	---
5.0	2.6	8.30	70			
6.0	2.1	8.72	95	2.81	---	---
9.5	1.8	8.55	110			
10.5	0.5	8.85	82	6.34	47.5	9.3×10^{-2}
14.5	2.0	8.80	81			
15.5	5.7	8.62	114	8.89	---	---
19.5	0.6	8.89	75			
20.5	1.4	8.65	89	3.61	47.1	0.15
24.5	1.1	8.75	91			
25.5	0.9	8.75	80	18.38	42.6	.13
29.5	1.7	8.50	108			
30.5	2.4	8.78	90	38.39	---	---
34.5	1.3	9.15	64			
35.5	1.5	8.60	45	14.93	---	---
39.5	1.2	8.89	65			
40.5	1.2	8.95	60	21.59	44.6	0.16
44.5	5.5	8.49	124			
45.5	5.7	8.5	122	27.84	---	---
49.5	1.2	8.75	72			
50.5	.6	9.08	49	3.88	45.1	0.66
59.5	1.1	8.95	83			
60.5	.8	9.00	57	6.39	---	---
68.5	1.1	8.88	82			
70.5	.6	9.10	55	3.43	---	---
79.5	2.0	8.81	75			
80.5	1.2	8.90	64	14.72	---	---
89.5	1.5	8.55	120			
90.5	1.4	8.60	101	29.73	47.5	1.2×10^{-2}
99.5	.8	8.81	76			
100.5	.6	9.15	53	---	33.0	1.8
109.5	2.0	9.09	85			
110.5	3.6	8.85	95	27.53	---	---
120.5	4.5	7.85	69	---	---	---
130.0	2.4	8.70	75	32.9	39.35	---

[1] Milligrams nitrogen per kilogram of sample

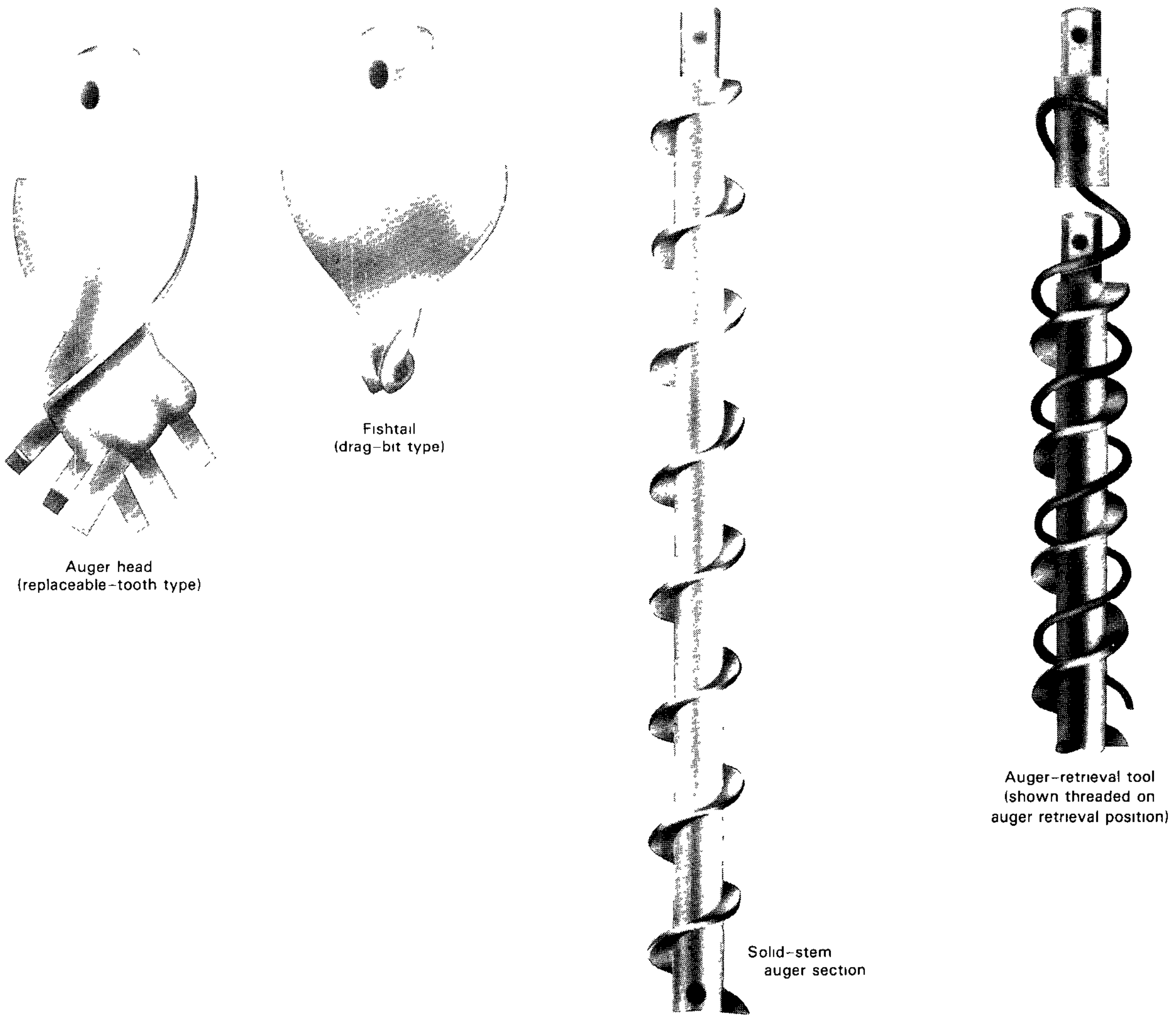


Figure 1.—Solid-stem augering tools: auger heads, auger section, and auger-retrieval tool.

Equipment and Accessories

Solid-Stem Augers

The basic equipment and accessories for solid-stem auger drilling are: lengths of solid-stem auger (usually in 5-ft lengths with auger-whorl diameters ranging from about 2 in. to as much as 12 in.), a drill head with replaceable bits, spring pins or similar means of connecting the auger sections, an auger holder or "catcher," a pointed hammer (such as a geologist's pick hammer) to drive connecting pins in or out, and an auger retriever or fishing tool. Some of these tools are shown in figure 1.

Hollow-Stem Augers

Hollow-stem augers are manufacturered in a variety of diameters, both I.D. (inside diameter) and O.D. (outside diameter), and in a variety of coupling designs. Some are made with threaded joints for coupling, and others use splined connectors with a removable, threaded set screw for transferring tensional loads. A center-rod assembly, consisting of a rod-to-cap adaptor, center rod, center-assembly plug, and a pilot bit, is used with the hollow-stem augers. Other necessary components for hollow-stem auger drilling include: a drive pin, an adaptor cap, threaded capscrews, O rings, an auger head with replaceable cutting teeth, and an auger holder.

Techniques for On-site Auger Drilling

Solid-Stem Auger Drilling

After a drill site is chosen, brush, twigs, and rocks need to be cleared from the rig area to allow safe walking and tool-handling access around the rig. Prior to spudding in the lead auger section and drill head, the immediate ground area needs to be cleared of grass and debris. A clean perimeter is established around the hole for depositing the auger returns when samples of the penetrated materials are collected. Use of low gear on the rig transmission and a moderate throttle setting usually provides sufficient safe power for drilling under any conditions. When spudding in the first few sections of augers, good practice is to rotate the augers as few turns as possible, while maintaining a firm downward pressure. This practice will start the hole straighter and decrease caving and widening at the mouth of the hole. If a faster rotational speed and less downward pressure are used, the augers tend to whip the upper part of the hole and widen it. If the hole is widened too much in the upper part, auger returns from greater depths will not be deposited at the surface but will keep falling back in the hole; if this occurs excessively, the augers will become bound in the hole. Assuming that the hole has been started satisfactorily, it is augered to the desired depth by progressively adding successive flights of augers. Hole depths that can be reached vary considerably from project to project depending on operator expertise, size and type of the rig, auger-flight diameter, pitch of the auger, the type of drill head and bits, and the materials encountered. Due to the large number of variables, setting arbitrary depth limitations for auger drilling is difficult. The industry commonly uses a depth limit of 100 ft, but holes have been auger drilled and observation wells installed to depths of 300 ft in coastal-plain sediments, using 5-in. solid-stem augers.

Hollow-Stem Auger Drilling

Hollow-stem augers usually are used for soil-sampling projects. Hollow-stem auger drilling allows drilling and casing of a hole simultaneously, thereby eliminating hole-caving problems and contamination of soil samples collected through the bottom of the auger head. The hollow-stem auger drilling and sampling method is one of the best means for collecting uncontaminated, repre-sentative, and even undisturbed samples of shallow, unconsolidated formations. This method is unsurpassed for collecting samples in a contaminated environment, such as around solid-waste pits, pesticide dumps, nitrate-contaminated zones, TNT (trinitrotoluene) spills, and radioactive-waste-disposal areas.

Hollow-stem auger holes have been drilled and drive samples collected using 7½-in. spline-connected hollow-stem augers to depths of nearly 200 ft in alluvial deposits containing gravel and even boulder zones. Some of the types of data that can be collected by the hollow-stem auger, drive-core method are shown in table 2, which also indicates the depths at which the data were obtained. With careful selection of drill tools, using proper auger-drilling techniques, results can be rewarding, and data can be obtained relatively inexpensively compared to drilling by other methods.

The actual mode of penetration using hollow-stem augers is basically no different than that previously described for solid-stem auger drilling. A major tool difference, however, is the hollow-stem auger has a center rod and pilot bit that cut the center part (3¼ in.) of the hole (fig. 2). In practice, then, both the 5-ft section of auger and center rod need to be added after each 5 ft of material have been penetrated. At any sample depth, the center rod with the pilot bit attached to it is simply withdrawn; the sampler is fastened to the center rod and lowered to the bottom of the hole for sampling. After the sample has been collected, it is returned to the surface; the pilot bit and center-assembly plug are reattached to the center rod and reset in the augers. Auger drilling can then progress to the next sampling depth where the procedure can be repeated.

Auger-Drilling Procedures and Problems

This section is intended as a guide for an inexperienced operator to some of the techniques, problems, and problem solutions in auger drilling. In pointing out the advantages of auger drilling as a fast and easy method for shallow exploration in unconsolidated materials, the authors do not mean to instill a false sense of ease in the operator. Like any other type of drilling, auger drilling posses problems, and it requires effort and expertise for successful results.

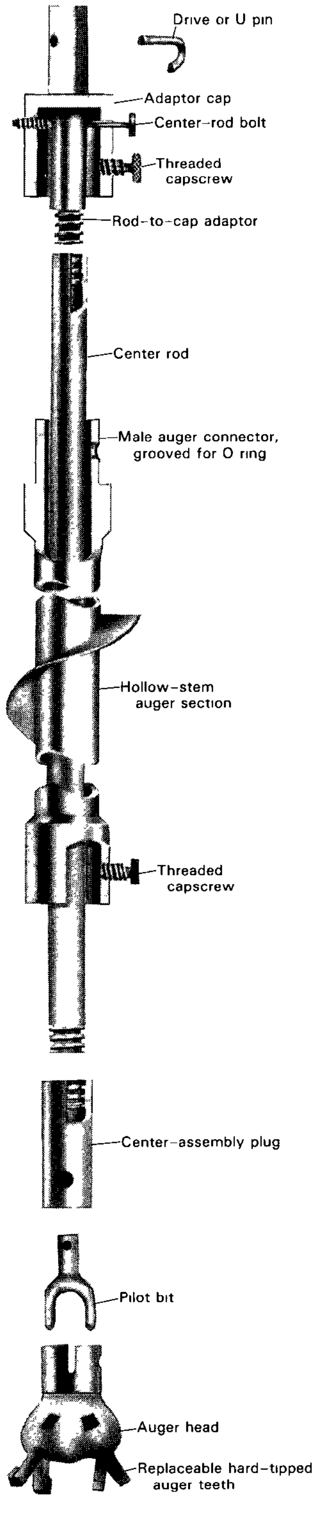


Figure 2.—Hollow-stem auger section with center-rod assembly and accessory components.

Auger Drilling in Moist or Saturated Materials

Auger drilling in moist or saturated materials usually can be done at a rapid penetration rate. However, ease of penetration, resulting in a possibly very fast drilling rate, poses more problems than advantages in auger drilling. An inexperienced operator is inclined to make a hole as fast as the auger head will penetrate the formation, even though one should not drill into formations any faster than the drill cuttings can be delivered up the auger flights to the surface. If the penetration rate exceeds surface returns of the cuttings, then trouble and lost time ultimately will result. Generating cuttings faster than they can be returned to the surface causes the cuttings to: (1) become solidly packed between the auger flights, prohibiting the newly penetrated material from moving up the auger or (2) be forced back into the hole wall if it is soft enough. Thus, the sample is not getting to the surface for lithologic identification, and a binding situation can occur later.

Assume that a typical alluvial or glacial-type material containing sand, silt, and clay zones or a mixture of these materials is being drilled. Further assume that a clay bed of a few feet thick has been encountered and the auger will make a nice bit-size smooth hole through this clay bed. Clay, particularly moist clay, is easy to distinguish when auger drilling because it has a tendency to pull the auger head in and pull down on the rig.

If a soft sand or sand-gravel mixture below this clay zone is encountered and the penetration rate of the augers is increased, many more cuttings than can be passed through the tight hole in the clay zone will be made which will create a sand lock (wedge), prohibiting any of the lower cuttings from moving up the hole. This phenomenon usually can be identified when it occurs by a sudden pull-down on the back of the rig and a noticeable laboring of the rig engine. Increasing engine power in an attempt to force some material through the restriction could result in twisting off the augers somewhere downhole. Generally, the augers can be freed by shifting the drill-rig transmission into reverse, exerting a substantial downward pressure on the auger, and slowly engaging the clutch to break loose and move the augers downward. If the augers do not come loose, try to move them slightly by alternately

Table 2.—Data from drive-core samples collected from a hole drilled using a hollow-stem auger

[ft, feet; µmho/cm, micromhos per centimeter at 25°C; mm, millimeter]

Depth (ft)	NO_3—N[1]	pH	Specific conductance, µmho/cm	Soil moisture (percent by volume)	Porosity (percent)	Median grain size (mm)
7	13.9	8.6	137			
8	8.6	8.25	46	5.67	37.9	0.41
17	9.6	8.82	84			
18	23.6	8.87	142	7.52	39.0	0.28
27	22.2	8.71	105			
28	30.0	8.59	157	2.66	32.2	0.92
37	6.7	8.80	87			
38	3.5	8.90	68	2.22	27.0	1.1
47	4.3	8.82	73			
48	2.6	9.01	50	2.47	---	---
57	2.6	8.90	71			
58	4.7	8.91	63	4.22	28.6	0.64
67	2.0	8.70	71	2.47	---	---
77	1.6	8.81	62			
78	3.3	8.51	60	3.88	36.8	0.40
87	1.5	8.75	85			
88	1.5	8.95	53	4.09	---	---
97	1.1	9.01	58			
98	1.5	8.55	118	3.18	32.7	0.93
107	1.3	8.88	79			
108	0.9	9.10	53	4.10	---	---
117	1.5	8.70	71			
118	1.2	8.90	43	3.96	39.7	0.32
127	1.1	8.81	85			
128	1.1	9.01	50	3.55	---	---
137	1.2	8.90	39	3.23	34.4	0.53
157	1.0	8.50	39	3.67	---	---
185	1.5E	8.70	77	---	---	---

[1] Milligrams nitrogen per kilogram of sample

engaging and disengaging the clutch. The augers may move only a fraction of an inch; continue the process and the augers will almost always be freed. Once the augers have been freed, reinsert them in the hole, using reverse rotation until reaching the bottom. Now, alternately raise and lower the augers, continuing reverse rotation and attempting to dislodge the material between the auger flights. Observe where the bottom is encountered by alternately raising and lowering the augers. If the material is coming off the augers, the top of the cuttings will be elevated as the operation progresses.

Verify that the sand lock has been broken loose from the augers by disengaging the clutch and deadsticking the augers up through the restrictive clay zone. If the augers move freely through the previously blocked area, lower the augers to the top of the cuttings, engage the clutch in a forward gear, and slowly move the cuttings up through the tight area. When the reintroduced cuttings have been removed from the hole, continue auger drilling, remembering not to penetrate the formation at a rate that exceeds the capacity of the auger flights to carry the cuttings through the restricted part of the hole.

A similar problem that may occur while auger drilling is large gravels or cobbles locking up between the auger flights and the hole wall. This usually occurs after passing through a gravel bed. In auger drilling, particularly under saturated conditions, gravel or cobbles are not drilled but are pushed aside. During further auger drilling, either some material moving up the auger or one of the auger flights will dislodge the rock from the side of the hole. If the rock is small enough, it eventually will move to the surface; however, it can get caught between an auger flight and a hard wall section. This results in no drilling action, very similar to the previously described sand-lock problem. The best method to solve this problem is to reimbed the rock in a soft section of the hole wall in the following manner: (1) shift the rig transmission into reverse and dislodge the rock by alternately engaging and disengaging the clutch; and (2) after the rock has been dislodged, with the auger still in reverse, reinsert the auger down the hole and try to reimbed the rock in a softer wall section by alternately turning the augers one or two turns forward and one or two turns in reverse while, at the same time, imparting a slight downward thrust on the augers. This technique sounds complicated; however, experience has proven that it usually works.

The authors refer to using relatively slow revolutions per minute (usually first and second gear) during auger drilling, particularly when most auger-drilling rigs are equipped with five forward speeds. Industry literature suggests shifting to high gear and increasing the throttle setting to spin the cuttings to the surface. From experience gained by drilling hundreds of thousands of feet of holes by the auger-drilling method, we have learned that very rapid revolutions-per-minute auger drilling can result in many problems, such as enlarged holes and lost connecting pins and bolts from vibration, which results in lost augers. The higher gear ratios on power-auger transmissions may be valuable in hydraulic-rotary rock coring, but they are not appropriate for auger drilling in unconsolidated material. Even when auger drilling in saturated conditions, rapid auger drilling will only accomplish the pumping out of gigantic mounds of caved or viscous sands from some unknown depth. An appropriate method for auger drilling in moist or saturated materials is to use a moderate throttle setting with the rig transmission in first or second gear; exert enough pressure on the hydraulics to penetrate the formation at no faster rate than cuttings can be transported up the auger flights; and log the hole by feel of the drilling action, along with geologic observation of the returned cuttings, remembering that these cuttings are a mixture of penetrated lithologies. Cuttings returned to the surface, when auger drilling below the water table, can come from any place in the hole and are meaningless for sequential lithologic interpretation.

In the process of auger drilling under saturated conditions, the auger penetrates sand, silt, and clay layers, and rind or filter cake will form on the wall of the hole and will prevent loose materials from falling off the wall or large caving areas from forming. The hole then can be successfully cored and an observation well installed if the above-described augering procedures are followed.

Auger Drilling in Dry Materials

General problems encountered and possible solutions, such as for sand and gravel locking mentioned in the previous section, are also possible during auger drilling in dry materials. However, one particular problem is poorly understood and requires special attention. When auger drilling in nearly dry lake beds (playa deposits) or similar type sediments (commonly found in the arid western part of the United States), heat is generated in the drilling action through friction of the material trying to move up the auger flights in a dry and close-tolerance hole. The materials actually bake on the augers and auger head to a consistency that cannot be penetrated; the auger head teeth are unable to cut the material, and the material will not move up the auger. The hole wall is so competent that the material being cut by the teeth has no place to go, and penetration refusal is reached. Most operators assume they have hit rock, because it feels and sounds like rock (a screeching and grating sound emanates from the hole).

Remove the auger when this situation occurs, and clean the lower few whorls of the auger if they are completely covered with this baked material, which is so hard that it may have to be removed with a geologist's pick or chisel. When the augers are reinserted in the hole, drilling will progress until enough heat is generated to result in a repetition of the problem. Note how to recognize and remedy this problem. When this baking-on occurs, a semihard obstruction forms around the augers that functions like a brake band. A sudden change in the sound of the engine on the rig would indicate this problem; the engine labors and might even stall. Disengage the clutch immediately and stop the auger rotation; notice the backlash in the augers at this time from the torque imposed on them. Relieve the pull-down tension and cautiously and slowly reverse the augers' direction, thereby unscrewing them from the tight material. Continue this procedure until the lower flights of augers are free from the obstruction; then resume drilling at a moderate speed and advance the augers slowly back into the material, allowing the auger teeth to break up the cakey zone of sediments and transport them up the auger flights. If necessary, pour several gallons of water into the hole around the augers, as they are rotating, to cool and break up these sediments and free the augers for drilling. However, prior to pouring any water down the hole, check with the person in charge of the drilling program to see if the water is going to have any deleterious effect on later sampling for moisture content. If augering with a hollow-stem auger, one technique for destroying this baked-on material is: remove the center-assembly plug and lift the auger about 5 ft; pour in enough gravel (1- to 1½-in.-diameter, crushed preferred) to fill the bottom 5 ft of the hole. Reinsert the center rod and center-assembly plug and slowly drill into the gravel; the gravel has a tendency to remove the baked material from the auger. Try any or all of these techniques depending on hole conditions. If none of these techniques is successful in dislodging the caked or baked-on plug at the auger head or between the auger flights and the auger will not penetrate, remove the entire string of augers and remove the material that caused the obstruction, repeating this technique whenever necessary.

Although the authors stress slow rotational speed of the auger for drilling moist or saturated formations, we also must emphasize it for dry materials because faster rotational speed increases the heat generated by friction, and heat is the major problem here. For example, a problem encountered in drilling dry lake-bed materials and solutions to the problem follow: An experienced auger-drill operator was attempting to drill and collect drive-core samples at 5-ft intervals to a depth of 100 ft. After destroying three clutches on the rig to reach a total depth of 50 ft in several days, the operator was sure the materials were too hard for auger drilling. However, because of a critical need to obtain the core samples, another extremely knowledgeable operator was sent to assist in the operation. His observation was that the operator was drilling at a far too rapid speed, resulting in a high-heat baking of the materials on the auger. His first recommendation was to drill the hole using first gear, with the throttle set at a fast idle. The result, using his suggested method, was a 1-day completion of a 100-ft hole, collecting drive-core samples every 5 ft.

Drill Response in Various Lithologies

The following discussion lists some reactions of a drill to various lithologies penetrated with ease or difficulty, that may help an operator determine what type formations he is drilling in.

1. Sands: Relatively easy drilling, smooth auger rotation, and fast penetration rate. If sands become dense, penetration rate decreases and the back of the rig may lift slightly.

2. Sands and gravel: If sands and gravel are encountered below the water table and the gravel-size is small (1-in. diameter or less), a slight vibration may be felt as the auger teeth encounter the gravel. As gravel size increases, the chatter or vibration of the auger increases. If this lithology is encountered above the saturated zone, the vibration is much more pronounced.

3. Silts and silty clays or clay silts-dry (playa-lake deposits): Slow auger rates (particularly in indurated material) may cause considerable chatter of augers; cuttings may become extremely hot; and a screeching sound may be caused by auger rotation. Rig engine will labor or even stall from the augers binding in the hole. Very few or no cuttings are returned to the surface. Remedial steps may have to be used if penetration is to be successful.

4. Silts and silty clays or clay silts-wet (playa-lake deposits): Smooth, fast auger penetration. Augers may dig in in moist clay-silt formations and pull down if auger penetration is too fast. Cuttings may come to the surface shaped as cohesive balls or cones of various sizes. Cutting returns to the surface may occur erratically or not at all in some instances. If these materials are completely saturated, the penetration rate increases, and cuttings returned to the surface are the consistency of a milkshake.

5. Clays-dry: Auger drilling characteristics are similar to those of dry silts.

6. Clays-moist: Easy penetration. They will exert a definite pull-down on the back of the rig if penetration rate is too fast. If penetration rate is not too fast, the material will stick between the auger flights. Slower penetration will result in the cuttings returning to the surface with a texture like ropey modeling clay. If the clay is completely saturated and sticky, it will adhere to the augers, resulting in no returns.

7. Caliche, friable soft sandstone, and siltstone: If these materials are dry, they will cause a chattering similar to gravel and will also have a tendency to cake on the auger, similar to dry silt. If they are saturated, they will have characteristics similar to tightly compacted sands.

8. Boulders: When large boulders are encountered, a pronounced chattering and hammering of the augers occurs with a high-pitched screeching of the auger teeth as they try to cut the rock.

Retrieval of Lost Augers

Nearly everyone operating an auger-drilling rig for any length of time eventually is going to lose an auger down the hole. Several methods exist for fishing and retrieving lost augers; these methods may or may not be successful depending on the condition and equipment available for conducting the operations. The usual cause for loss of an auger is that someone forgot to put in a coupling pin or the pin has lost its temper from metal fatigue and is vibrated out. Or, in the case of hollow-stem auger coupling, someone did not put in the threaded capscrew or forgot to tighten it. If these omissions occurred and the auger drilling progresses, when the augers are retracted, the auger flights are separated. On some occasions, welded upper or lower shanks of the augers simply part from weld or metal fatigue. Whatever the reasons for separation, some of the auger is left in the hole and needs to be retrieved. One or more of the following fishing and retrieval methods should be successful. The first question that is asked when auger separation occurs is: What happened? The only answer is: Pull the remaining auger to examine it. Assume that, after auger drilling with a 4½-in.-diameter solid-stem auger and returning it to the surface, the bottom shank is still in place. Then, the problem is that the U pin either was not put in, was inserted backwards, or somehow came out. The first step, prior to the fishing attempt, is to use a sounding weight to see if any cuttings are in the hole that have buried the top of the 1⅝-in. hex shank on the top of the auger. If cuttings or caved material are on top of the lost augers at the time of sounding, first remove this material by using a wash pipe and washing the sloughed material out of the hole.

If the top of the auger can be sounded, proceed with the fishing operation. Carefully lower the recovered sections of the augers back down the hole without rotating them, until they come in contact with the augers in the hole (the fish). The hex connectors unlikely would be aligned, so attempt to align them by exerting a very light downward pressure with the rig hydraulics while, at the same time, slowly turning the drive spindle (with a pipe wrench if possible). When the mating hex shanks are aligned, the augers will drop slightly. As soon as this occurs, stop any rotation. Now, slowly begin retrieval operation by lowering the hydraulics until the augers are butted tightly together. The augers are now reconnected, but no U pin is in them so they cannot be merely pulled out. However, they can now be screwed out of the hole. Shift into reverse gear, begin slowly rotating the auger, and decrease pressure on the hydraulics at a rate equal only to the upward thrust exerted by the augers. This upward thrust will try to lift the back of the rig; this can be seen to occur, so it is not difficult to keep the hydraulic retraction rate equal to that of the reversing augers. After the augers have been reversed out to the point where the U pin was missing, set the augers down on the auger holder and insert a connecting pin.

If the connecting bolt was lost when drilling with hollow-stem augers, the same procedure for getting back onto the fish, and then reversing the augers out to retrieve them, would be applicable. The only difference in solving this problem when drilling with the hollow-stem auger would be in that instance where cuttings filled the hole above the lost auger. Instead of using a wash-out pipe, simply connect to the top of the hollow-stem auger and flush through it to remove the cuttings.

Use of Auger-Retrieval Tool

A special tool is manufactured for retrieval of a lost auger; this tool (fig. 1) is a “corkscrew” device manufactured of high-tension spring steel, designed to turn onto the lost auger, with the whorls of the retrieval tool matching those of the auger. If the weld of an auger section breaks, either the top shank of one auger or the bottom shank of another, there is no connection such as described in the preceding section to attach to for unscrewing the auger from the hole. The kind of break can only be determined after first removing the string of augers that is still attached to the rig. Remove this part of the auger as carefully as possible to not leave any cuttings on top of the lost auger. Assume, in this instance, that the problem is not a lost bolt or U pin but rather an actual parting of a weld and the auger broken in two. The simple "reconnection and unscrew from the hole" method cannot be used. After removal of the auger, sound the hole to see if it is open to the fish by addition of other auger sections. This reinsertion of the retrieval tool needs to be accomplished very carefully because it has a very close tolerance fit to the size of the hole previously cut by the bit, and (as discussed before) a rind commonly will be on the hole wall that corresponds to the diameter of the augers that are slightly less than bit diameter. When the retrieval tool is started in the hole, lower it without rotation whenever possible. However, if resistance is encountered, rotate the tool very slowly and, with a minimum downward pressure, try to auger the rind or other obstacle material up past the whorls of the retrieval tool. Reversing the rotation of the auger while trying to get the retrieval tool down the hole will cause a lot of material to fall to the bottom and, as a result, the retrieval tool might not reach the lost auger. If the retrieval tool reaches the lost auger, you will feel a contact. The next step is to screw the retrieval tool onto the lost auger until the connection is tight. Then, try to retrieve the augers that were lost in the hole by first attempting to rotate the augers without pulling up on them; use first gear at a moderate power rate, no more than 1,000 r/min on the engine tachometer. If the auger rotates at this time, something similar to sand locking, or a boulder lodging between an auger flight and the hole wall, has occurred to break the auger.

If the augers will not rotate, exert a 1,000- to 2,000-lb downward thrust with the rig hydraulics while, at the same time, alternately engaging and disengaging the clutch to break loose whatever is binding the augers. If this does not loosen the locked auger, push down on the augers as hard as possible without lifting the rig wheels off the ground, but do *not rotate the* augers. If any downward movement is achieved at all, alternately apply up and down thrust with the rig hydraulics, being careful not to pull up too hard (2,000 to 3,000 lb) or the coil spring of the retrieval tool may break or straighten. If any up and down movement of the augers occurs, eventually they should break loose to a point where they can be removed from the hole by deadsticking. If the pull becomes too difficult, rotate the augers slowly in a forward gear if possible. Do not pull or torque the augers so hard that the retrieval tool breaks, leaving it on the top of the lost auger. If this occurs, another retrieval tool cannot be connected to the last auger and the string of tools probably are irretrievable. If the above method is unsuccessful in loosening the augers, the retrieval tool needs to be reversed off the lost auger and returned to the surface.

The decision to proceed will depend on the cost of the tools in the hole versus the estimated cost of retrieval by complicated procedures, in time, money, and effort. If only a few sections of hollow-stem auger are in the hole, such as four sections plus the bit, the equipment cost is more than $1,100 at current prices (1988). Assuming a 50 percent chance of recovery, more than several days in attempted recovery cannot be invested or recovery cost may exceed the recovered equipment cost. If 15 sections of hollow-stem auger plus auger head are stuck in the hole, the equipment cost is about $3,700. Then, as many as 6 or 7 days in recovery attempts could be invested.

Auger Retrieval Using Wash-Over Method

Sand locking or boulder lodging at some place on the auger may prevent recovery of the auger sections by the fishing tool. These obstacles must be removed before the augers can be freed, probably by a combination of washing and drilling over the augers. If there isn't any wash-over pipe on hand, contact local drilling firms to see if they have the correct size wash-over pipe (7 in. for 6¼-in. auger) available on a rental basis. If the rig has a mud pump and rotary capability, attempt the drilling-over method. We have used flush-joint, collarless casing successfully, although standard 7-in. collared casing also has been successfully used for this drill-over procedure. First, assemble the necessary components: (1) enough pipe to overdrill to the bottom of the lowermost auger section; (2) one cross over sub that mates from the kelly sub to the pipe; (3) one 7-in. collar torch cut in a sawtooth pattern, with hard-facing weld applied to the sawteeth for use as a bit;

and (4) one 20-ft joint of pipe, cut and threaded into two 5-ft and one 10-ft joints. Now, construct a mud pit to the approximate dimensions of 3-ft wide by 6-ft long by 5-ft deep; fill it with a mixed drilling fluid using 50-s (seconds) viscosity, high-yield bentonite. A fluid discharge pit needs to be cut from the top of the auger hole to the mud pit for fluid return.

Start the drill-over washing procedure. Connect the sawtooth cutting collar to one of the 5-ft sections of pipe and couple this section of pipe to the kelly sub. With the suction hose in the mud pit, engage the mud pump and, as soon as fluid comes out of the bottom of the pipe, rotate the pipe slowly while, at the same time, exerting just enough hydraulic downward pressure to force the pipe down the hole. The saw-tooth cutting collar will have to shave off some of the wall as the auger bit cut only a 7¼-in. hole. Note: Initially, no drill fluid will return to the mud pit because the existing auger hole will have to be filled with drill cuttings and fluid before any return can come back up the outside of the pipe. If the kelly is long enough, advance the bottom cutting bit to at least 20 ft, pull the kelly back, and remove the 5-ft section of pipe and sawtooth collar bit. Now, screw the sawtooth bit onto the 20-ft joint of pipe and set this back into the hole. Reattach the kelly sub and continue drilling and circulating drilling fluid as before. Some rigs may be equipped with a kelly that is too short to drill ahead far enough to use 20-ft pipe joints for each succeeding connection. However, in the list of equipment were 5-ft and 10-ft joints of pipe. By using combinations of these shorter joints with a shorter kelly, the pipe can be advanced to a depth such that, when the pipe is pulled back and the shorter joint removed, a 20-ft joint can be added and the string dropped back into the hole and again enable you to recouple the 20-ft joint. With this combination of subjoints, 20-ft pipe joints can be used even if the rig is equipped with only a side-delivery water swivel in the 5-ft-plus hydraulic ram movement. Be very careful in penetration rate and torque applied to the pipe. Standard casing, particularly threads, are not made to withstand much abuse and, additionally, whatever torque is applied to the threads with the rig later has to be uncoupled, using pipe wrenches and manpower. If the problem that caused the augers to break was a sand-lock, it may not be felt on the way down. If it was gravel or boulder wedging, however, it will definitely be felt, and patience is needed when drilling them out because the hard-faced bit is not a hard-rock bit. When the bottom of the augers has been reached, flush the hole for several minutes to remove as many cuttings from the hole as possible while, at the same time, building a filter cake on the wall of the hole that will keep any sand or rock from falling back into the hole.

Now, slowly remove the wash-over drill pipe from the hole. Each time a section of drill pipe is removed, pour or pump in an equal quantity of drill fluid to replace the volume displaced by the removal of the pipe to maintain a positive fluid head inside the hole to support the filter cake and prevent recaving of sand, and so forth. After the entire string of wash-over pipe has been removed, recouple the spiral auger-retrieval tool and the necessary 5-ft sections of auger to reach the broken-off section; screw the retrieval tool onto the lost auger (as previously described); and, in almost all instances, the lost augers can now be removed from the hole. As mentioned in a previous section, using the drilling-wash-over method may be too expensive to retrieve a few sections of auger, but it may be well worth the effort in recovering a string of tools worth several thousand dollars. As an indicator of retrieval cost, a 100-ft wash-over needs to be completed in about 1 day; add that cost to the pipe and tools needed for the retrieval attempt to assess the cost of the operation.

Auger-Drilling Precautionary Measures

The following precautionary measures are discussed to decrease the chance of losing augers in operator-controllable situations:

1. When solid-stem augers are used, check the spring-type U pins carefully. If they fit extremely loosely in the augers, they need to be tightened by hammering the U closed until they have to be driven into the auger-flight connection hole. Inspect the pin for any hairline cracks that might have developed along the U bend; if any cracks exist, discard the pin.

2. When the U-pin connector is installed in the augers, make certain that the pin is driven in with the spring part of the pin facing to the right or in the direction of normal auger rotation. If the pin is installed incorrectly (in the opposite direction of normal auger rotation), rocks and soil will be forced under the pin while drilling, causing it to fall out in the hole resulting in lost tools.

3. When either hollow-stem augers or solid-stem augers are used, thoroughly inspect the box ends and pin ends of the augers before putting them on the drill string and drilling with them. Generally, cracks will develop in the steel or in the end-attachment welds from metal fatigue and torque stress imparted to the auger while drilling. If any metal or weld failure is apparent, set the auger aside until it can be repaired. If information needed by the project requires the extra depth obtainable by using one or two faulty or questionable augers, connect these augers last, near the top of the hole where they can be observed. If they do break, the result will not cause a loss of tools downhole because the break or failure will occur near or just below land surface. If this happens, dig down to the break, attach a clevis or cable sling around the remaining augers, and retrieve the augers with the sandline.

4. When hollow-stem augers are used, always inspect the welds around threaded inserts. If indications of cracks or weld failure are visible, repair them before using. If the auger-connecting capscrew does not start or thread easily into the threaded insert by using only the fingers, retap the insert to remove any burrs. If the capscrew still refuses to start readily, check the capscrew and redress threads with the die or small file. Do not force it to thread with a wrench.

5. When connecting hollow-stem augers that do not butt together correctly (box and pin connection), inspect the internal keys in the box end and the keyways in the pin end. Periodically, these become burred and distorted during tight or chattering auger-drilling conditions, and they require dressing with a small file to make the augers go together smoothly. Also, inspect the nonthreaded bolt hole in the pin end of the auger for any bulging or bolt-hole elongation. Dress any internal or external bulge around the hole with a file to facilitate ease of auger coupling and ease of center-rod assembly removal (it would tend to hang up on the internal bulge). If the bolt hole appears extremely elongated, replace the pin end.

6. Before using capscrews to connect the hollow-stem auger flights, clean the threads thoroughly with a wire brush. Use a 12-gauge shotgun cleaning brush (wire type) to clean dirt and grit out of the threaded insert holes before threading the capscrew into it. Lubricate threads slightly with a light oil to prevent rusting; water needs to be used as a lubricant during drilling.

7. When drilling in gravels with a hollow-stem auger, if excessive chattering of the augers occurs, apply some nonhardening Permatex or similar material to the capscrew threads to prevent the capscrews loosening and falling out in the hole because of chattering vibrations.

In addition to drilling holes by the auger method for determining lithology and taking core samples, completing the hole as a temporary or permanent observation well for the purpose of collecting water samples also usually is desired. The following sections describe some of the many ways of installing well points in both solid-stem and hollow-stem augered holes.

Installation of Well Casing and Screen in Solid-Stem Augered Holes

The major problem with installing observation wells in a solid-stem augered hole is getting the screen or screened well point down through the caved material that usually results (particularly below the water table) when the augers are removed from the hole. The simplest method for installing a screen through caved or bridged material is: Couple a screened-drive point (fig. 3) to the bottom of a 21-ft section of whatever diameter of steel pipe is needed for the well, and lower it into the hole, adding whatever number of additional joints of pipe are needed until a point is reached at which the well point and pipe, by its own weight, will no longer penetrate the caved material. In many instances, the drive point can be pushed through the caved material by using rig hydraulics to push it to the required depth. If the caved material consists of relatively dense clean sand and the point cannot be pushed through, use the drive hammer ordinarily used for drive-core sampling. Note: If a drive hammer is used, the use of a drive-rod-to-pipe coupling will not damage the pipe threads. Although this is the simplest method for installing a screened-drive point through caved material, it is the least preferred method because the screen can be plugged with fine particles as it passes through the caved-saturated material. The hydrostatic head outside the screen will try to equalize to that inside of the pipe; this action may completely plug the screen slots resulting in a slow or nonresponsive observation well. Try to alleviate this problem by pouring water into the pipe, keeping it as full as possible to maintain a higher hydrostatic head inside the pipe than the hydrostatic head outside the pipe.

Two more appropriate methods for installing a screened well point through caved material, both requiring a pump and water supply, are:

1. Sound the test hole to determine elevation of the filled-in material, and insert the drive point to a depth of a few feet above that point. Now, couple the pump-discharge hose to the top of the well pipe and pump in clean water at a rate of 20–25 gal/min through the drive-point screen, while, at the same time, lowering the pipe and screen. This water will wash the material away from the drive-point screen so that it does not become plugged; at the same time, it will provide a lubricated annulus for the pipe to follow. Now, the only resistance to penetration is located in the bottom few inches of the tapered drive point; this resistance is usually overcome by the weight of the pipe. If resistance from either dense, clean sand or possibly some gravel that has bridged the hole is encountered, preventing penetration of the point, spud the point through the problem zone by alternately lifting and dropping the pipe string with the sandline winch. A drive point usually can always be driven through caved material by using this wash-in method; also, the screen will be clean and responsive to water-level changes in the aquifer (into which it has been installed).

2. Another method of installing a screened well point through caved material is using a so-called jetting point (fig. 4). These points are equipped with a spring-loaded ball-check valve that keeps material from coming into the screen from the bottom, while allowing pumping through the bottom of the screen for washing away material in the hole. The jet-type well point will allow wash-through in almost any restrictive conditions in the hole. It is particularly valuable used in conjunction with plastic-pipe well installations because no driving or abusive methods need to be used to penetrate the caved material.

Either of these two washing methods offers a good means of installing well points through caved materials in a solid-stem auger hole, and they offer the best possibility for providing an adequately responding observation well. One additional technique can be used to assure that the wells will be responsive to head changes in the aquifer. When required depth of the screen is reached, increase the pump discharge and vigorously flush the screen (a pressure exceeding 80 lb/in.^{2} may break the pipe if

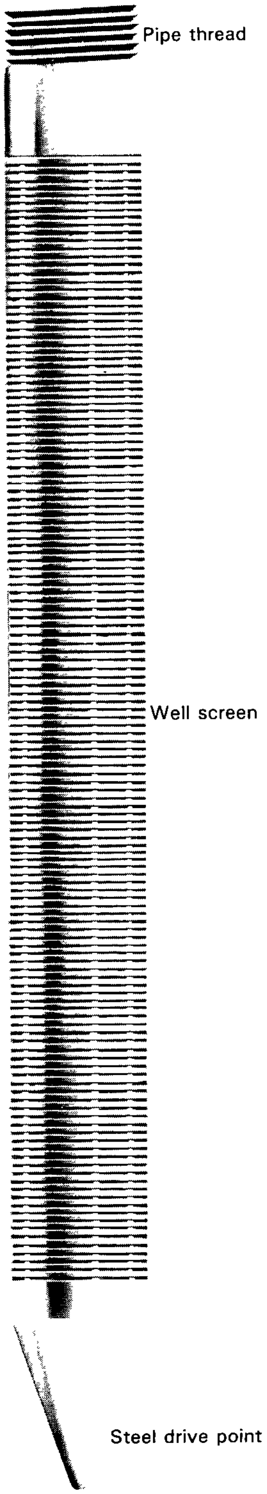
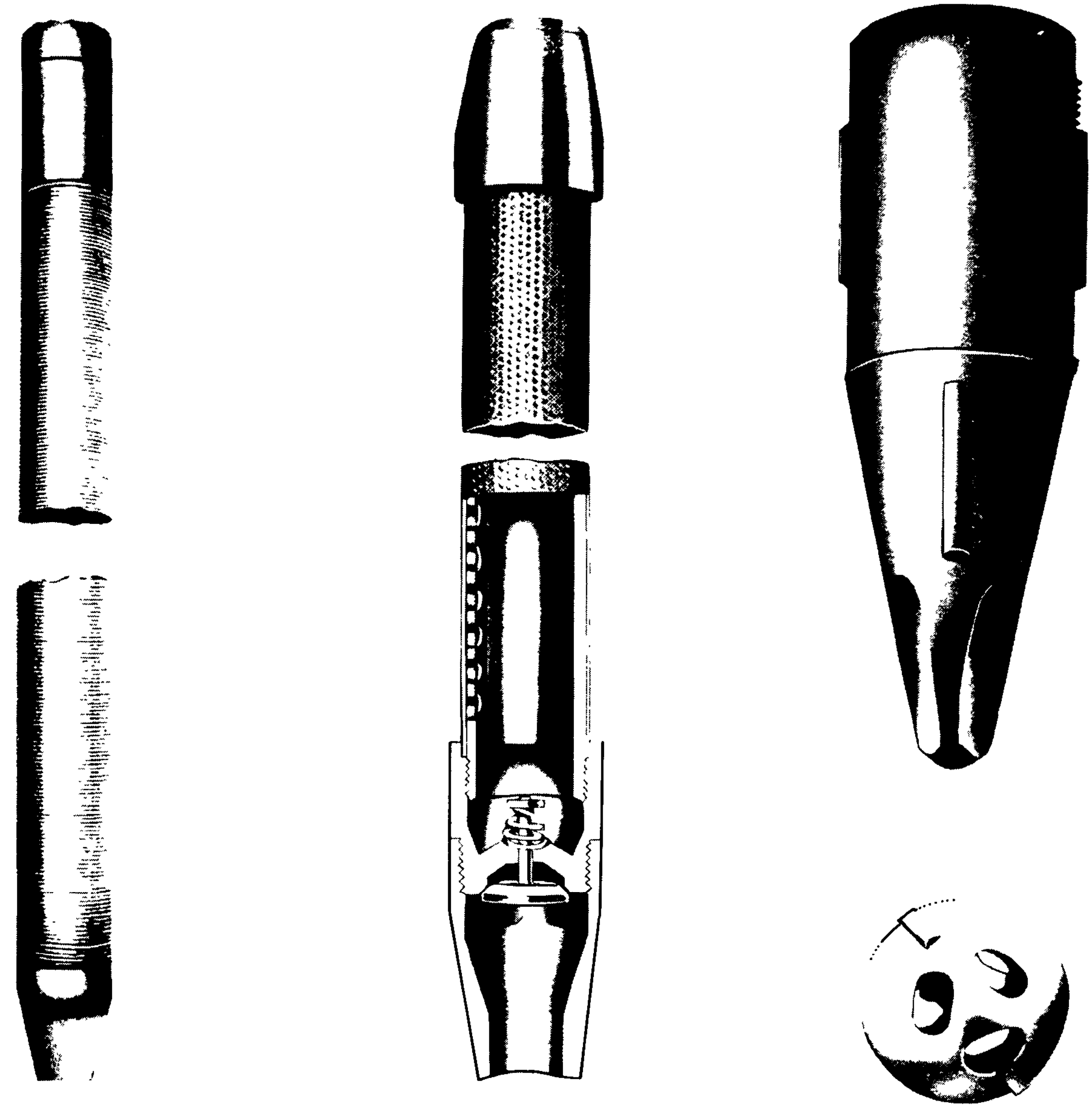


Figure 3.—Well-screen and drive point.



Continuous-slot type

Brass-jacket type

Jet head tapering-point

Figure 4.—Types of self-jetting well points.

plastic pipe is used). Do this for several minutes, and, as the screen flushes out, sediment around it will be agitated and lifted; shut the pump off and let the agitated cuttings resettle. Coarser cuttings will settle back first, resulting in a coarser sand pack around the screen. This continual gradational settling of finer materials out above the screen will lessen the possibility of vertical movement of water within the borehole.

Drilling-in of the screen is one additional method of installing well points and screen through caved material in auger holes. This method has special application in holes with a considerable quantity of dense sand or gravel bridging, through which the well point or screens cannot be pushed or driven, particularly where no means of water flushing is available. First, weld on either cutting blades or a gravel-removal spiral to the bottom of the screened points (fig. 5). These blades or spirals are constructed to open the hole to a point greater than the diameter of the screen, providing some protection to the screen, while at the same time providing room for (succeeding) pipe collars.

Lower the well screen on 21-ft joints of steel pipe into the hole until the dense caved material or gravel bridge is reached. Use 5-ft joints of pipe, coupled to the auger drive, by a 1 5/8-in. hex to male pipe-thread adaptor; slowly and carefully drill the screen in. Take special drilling care if large gravels are encountered because they can tear the screen; if large gravels are encountered, rotate the pipe very slowly. The drill wings or spiral tend to push the gravels back into the softer materials in the hole; however, some of them will move up beside the screen. If this occurs, too fast rotation and penetration rate can result in serious damage to the screen. If the auger is equipped with a side-delivery water swivel or some other means of water delivery, use it to aid in lubrication during installation, as well as keeping the screen slots open. Water can also be poured in the pipe to maintain a positive head inside the pipe as previously described. Although this method requires care because of the chance of screen damage, it can be successful; screens as large as 6 in. in diameter have been installed to considerable depths using the method.

Installation of Well Casing and Screen in Hollow-Stem Augered Holes

Installation of a screened well point through a hollow-stem auger is easier than the installation of a screened well point in a caved solid-stem auger hole. Assume a situation where the aquifer to be screened with a screened well point has been auger drilled using one of the methods to keep cuttings from coming up inside the auger, described on pages 57 to 58. Also, suppose a drive-core sample has been taken at the bottom of the hole to verify that it is the desired aquifer material. Proceed with a simple method that will usually result in the installation of a very clean, responsive observation well. Lower the pipe with screened drive point attached to the bottom of the hole. If the method for holding out fill-in of the auger by caving materials was the hollow-stem auger filled with viscous fluid technique (see p. 57 to 58), the viscous fluid needs to be pumped out of the hole by attaching a discharge hose to the top of the pipe and pumping clean water through the screen. After flushing, disconnect the hose; fasten a pipe to the drive-hammer-rod connection and, through the use of the drive hammer and cathead, drive the screened well point into the aquifer material. Another excellent method of installing well points through a hollow-stem auger, where viscous sand fills up the inside of the hollow-stem auger, is described in a written communication by P. A. Lutin, A. E. Coker, and R. R. Pemberton (1967). The following quoted material from the communication provides the essential concept.

> The desired length of casing was measured from the tip of the well point and the plastic pipe was cut with a knife.
>
> The length of plastic pipe plus the well point was such that with a plastic adaptor, coupling, and 5-foot section of galvanized iron pipe, the total length of the assembled casing exceeded the depth of hole by about 2 feet, thereby leaving a 2-foot section of galvanized iron pipe above the land surface.
>
> In some areas of Florida, drilling in the unconsolidated sediments above the limestone bedrock was troublesome because quicksand continuously filled the hole. When quicksand was encountered, a spare coil of plastic pipe was unrolled and fitted with a wash head, and the effluent end of the pipe was inserted through the auger stems to wash the hole free of sand. The spare plastic wash pipe could be removed and the assembled plastic well casing inserted in the sand-free hole in a matter of seconds.
>
> After the well casing had been installed, the auger was removed, the hole backfilled, and the-section of steel pipe was cemented in for stabilization. It should be noted that flexible plastic pipe is used for this method of installation.

If installation of observation wells in hollow-stem auger holes is to be accomplished in the open hole or at some depth other than through the bottom of the auger, then the methods described on pages 13 to 16 are applicable.

Throughout the description of installing observation wells in auger-drilled holes, the authors have stressed the importance of keeping the screens clean so that the well will respond quickly and accurately to water-level changes in the aquifer. A poorly responsive observation well will provide erroneous data. Any observation well or water-sampling point that is installed should be checked immediately to ensure that it is open and responsive to the aquifer by running a slug test to determine specific capacity, or, if some means of pumping the well is available, it can be checked for yield. If the well point is not adequately responsive, remedial

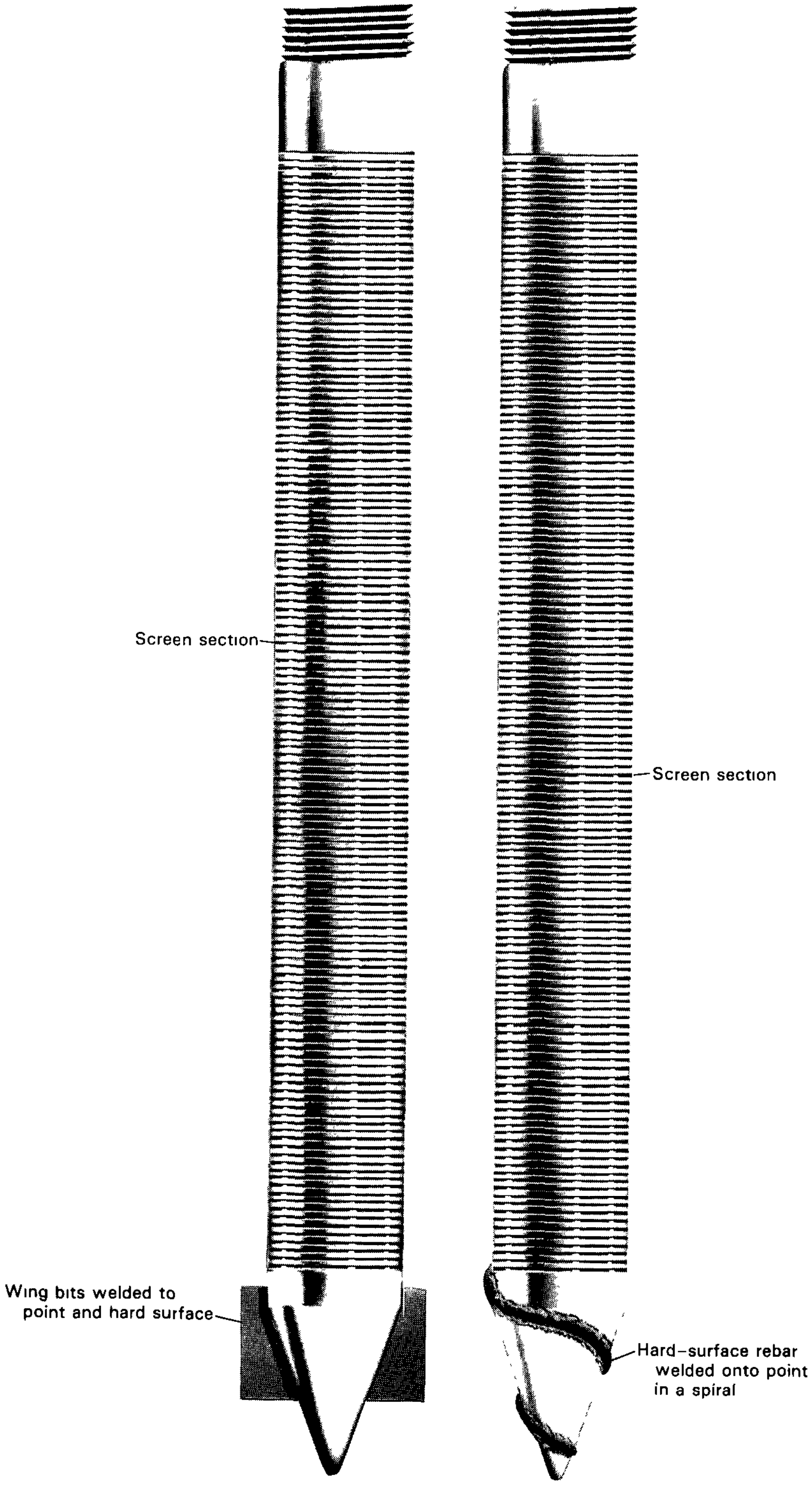


Figure 5.—Drilling drive-point-type well screens.

development procedures must be used to correct the problem. Methods for development of small-diameter wells are described beginning on page 85.

Hydraulic-Rotary Drilling

Applications of Hydraulic-Rotary Drilling

A high percentage of holes drilled for oil, gas, and mineral exploration is drilled by the hydraulic-rotary method as is an ever-increasing number of standard test holes and water wells. Although the cutting samples from hydraulic-rotary-drilled holes are usually not any more contaminated than those obtained from cable-tool drilled holes, and water wells drilled by the hydraulic- or mud-rotary system require more development effort, the method is still gaining in popularity because it is economical. In drilling unconsolidated sediments and hard rock, other than cavernous limestones and basalts where circulation cannot be maintained, the hydraulic-rotary method is a faster and usually more economical drilling method than the cable-tool method. The Water Resources Division of the U.S. Geological Survey uses the hydraulic-rotary method for a high percentage of its contract drilling of test holes. However, the kinds of data and quality of data that should be available from this type of drilling are often not obtained, so this section of this manual offers some remedial techniques.

A basic but detailed description of drilling mud is provided to assist the reader in understanding this very important aspect of hydraulic-rotary drilling. Mud control, particularly in shallow test-hole drilling and in the installation of water wells, is the most important factor to be considered in hydraulic-rotary drilling. Mud control is of paramount importance in hole control and conditioning of the hole for later geophysical logging because borehole-geophysical logs must be run in a rotary-drilled hole to get maximum data from the hole. In addition, mud control is of vital importance in the drilling of water wells (both observation and production); a proper filter cake must be formed on the wall to prevent harmful invasion of mud into aquifers. The mud must later be removed from the aquifer in the development process of the completed well.

The petroleum industry drills into producing zones that may be orders of magnitude less permeable than many of the shallow ground-water aquifers with which the U.S. Geological Survey is concerned. Yet petroleum companies design elaborate mud programs maintained by mud engineers to prevent invasion, while many other persons involved in ground water almost totally ignore the problem. The purpose here is to emphasize the importance of mud control in the proper collection of samples from mud-rotary-drilled holes, as it has great significance in mud-rotary coring (see p. 37).

Equipment and Accessories

The basic equipment and accessories of a hydraulic- or mud-rotary drill are: a derrick and hoist, a mechanically or hydraulically operated pull-down and holdback system, and a revolving table through which slides a square or fluted kelly that turns the drill pipe and allows it to move downward as it is turned. The string of drill pipe is usually equipped with heavy drill collars at the lower end to provide weight and stability to the drilling tools. A cutting tool or bit attached to the bottom end of the string of pipe and a pump forces drilling fluid through a water swivel and down through the string of drill pipe. The entire system is engine powered.

Methods of Drilling

Drilling is accomplished by circulating fluid through the bit, while rotating and lowering the string of drill pipe. The bit cuts and breaks up the material as it penetrates the formation, and the fluid picks up the materials generated by the cutting action of the bit. This fluid, with cuttings contained, then flows upward through the annular space between the drill pipe and drill hole carrying the cuttings to the ground surface, thus clearing the hole. The string of drill pipe and bit move downward, deepening the hole as the operation proceeds. After the drilling mud reaches the surface, it flows through a ditch or affluent pipe to a settling pit where the cuttings settle to the bottom. Cuttings are sometimes run through a shale shaker for removal of the larger particles. From the settling pit, the fluid overflows into the main pit, from which it is picked up through the suction hose of the mud pump and recirculated through the string of drill pipe.

The following three articles are suggested as references for those readers who want further reading on the subject: “Rotary Drilling

Handbook" (Brantly, 1961); "Ground Water and Wells" (Universal Oil Products, 1966); and "Water Well Technology," (Campbell and Lehr, 1973).

Drilling Mud

Three general types of drilling fluids are: (1) water with either native clays or commercial, high-yield bentonites added; (2) mud-laden, oil-base mixtures; and (3) air. Mud-laden, oil-base muds have no applications in drilling for ground-water investigations; and air, as a drilling fluid, is discussed on page 29.

Drilling mud serves to: (1) remove the cuttings generated by the cutting action of the bit from the bottom of the hole; (2) cool the bit and lubricate the bit bearings if the bit is the roller-cone type; (3) build a filter cake on the hole wall preventing fluid loss in mud invasion of penetrated formations; (4) support and prevent caving of the wall of the hole; (5) control the formation pressures of water or gas preventing these fluids from coming into the hole; and (6) lubricate the string of drill pipe as it rotates in the hole. These purposes are not listed in any order of importance.

Many problems encountered in mud control result from a lack of understanding of the terms used in describing drilling muds. For example, many people think of viscous mud as a weight property of the mud instead of a property of mud thickness (fig. 6). However, a viscous mud actually can be only slightly heavier than water; conversely, a heavy mud might be low in viscosity. These differences are important when considering desired purposes of the drilling mud in a drilling program. In general, use the lightest weight drilling mud possible considering the formation pressures and caving problems that may be encountered. The lighter weight muds will result in shallower invasion of permeable zones, thus permitting easier development of the aquifer upon completion of the well.

Unfortunately, many drillers feel that by keeping the drilling fluid thin, less damage and aquifer invasion by the mud will occur. However, this often is not the case and the reverse is true, because thin or low-viscosity muds containing 10–15 percent solids by weight may be composed mostly of heavy sands, and considerable invasion of the aquifer and washing of the hole wall will occur prior to the buildup of a filter cake. Also, a heavier, thicker mud cake will eventually form from filtration. An example of loss of hole control from using a thin native mud as compared to using a prepared viscous mud, is demonstrated in figure 7. Observe where the difference in the borehole rugosity is shown in the comparison of caliper logs of two holes drilled close together in the semi-unconsolidated Ogallala formation in western Texas.

The process that resulted in the two radically different holes drilled in the same lithology is shown in figure 7. Initially, the hole was to be used as a combination injection-production well, and the proposed procedure for completion was to drill through a 40-ft-thick aquifer (from 105 to 145 ft), install a screen through the entire thickness of the aquifer, case the hole to surface, and cement the annulus from the top of the screen to the surface. The screened aquifer was to be developed by the natural sand-pack method, using the bailing-surging-bailing, high-velocity jetting, and additional bailing method. No mud program was designed for the drilling of Hole 1. The drill contractor expressed assurance that, from prior experience in drilling, the use of clear water as a drilling fluid would soon result in the formation of an adequate drilling mud composed of a mixture of the water and natural clays contained in the formation. Unfortunately, this did not occur; enough natural clay was never encountered in the upper part of the hole to form a lightweight, viscous mud. As a result, the native drilling fluid rapidly washed out the loosely consolidated sand zones, and total circulation of drilling fluid was lost. Circulation was not restored even though circulation-loss materials were used. An attempt was made to cement off the zones of lost circulation and complete the hole as planned. Although the drill contractor was able to fill the hole up above the top lost-circulation zone, drilling out of the cement resulted in the bit breaking out of the cemented hole, and total circulation was again lost. After drilling blind (no circulation of fluid or cuttings to the surface) for a short interval, the hole was abandoned.

Prior to the start of drilling of Hole 2, a high-yield bentonite mud mixture with a marsh-funnel viscosity of 60-s and a weight of 8.55 lb/gal (pounds per gallon) was made. The hole was drilled through the previous zones of lost circulation, with no circulation loss and a minimum of fluid loss through filtration. Caliper logs of the two holes (fig. 7) dramatically demonstrate improved hole conditions resulting from the design and utilization of a

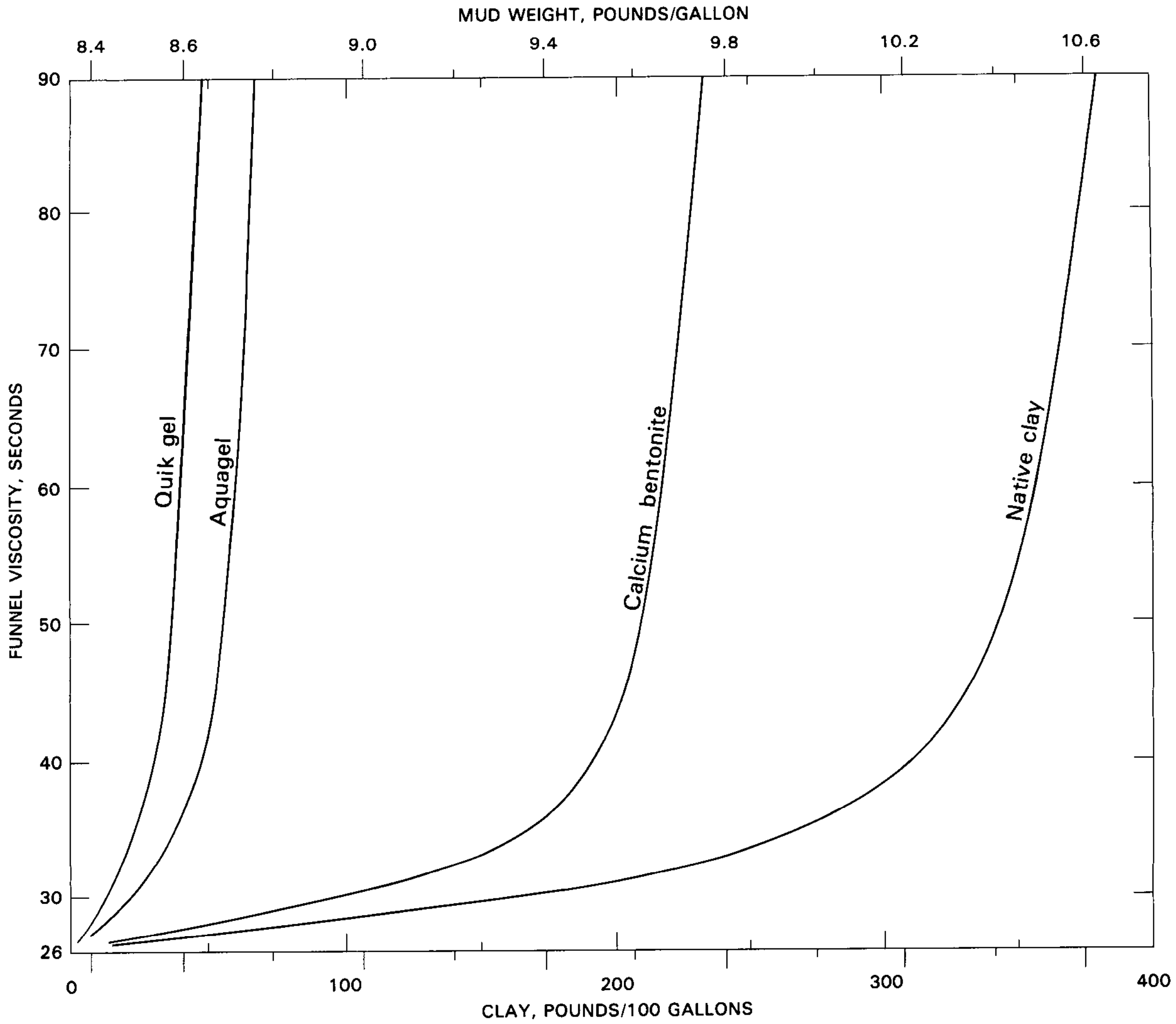


Figure 6.—Comparisons of mud weight versus funnel viscosity for various clays.

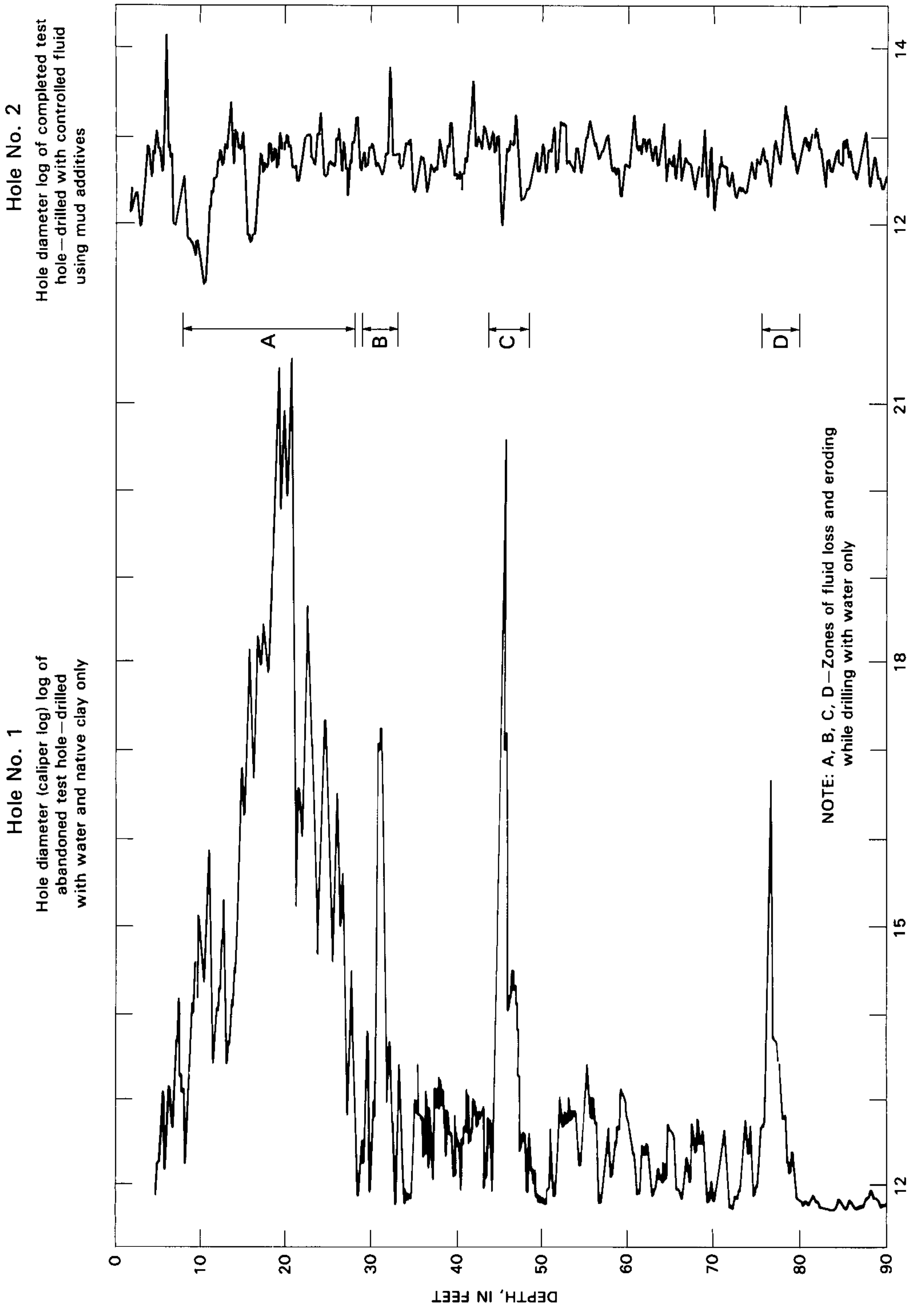
controlled mud program. The time to stop lost circulation and wash-out problems when drilling in unconsolidated granular materials is prior to start of drilling when the mud program is designed. Many examples of poor borehole conditions that result from the use of an improperly prepared drill mud are available, as demonstrated in figure 7. However, this example was used to emphasize the importance of proper mud control.

Instruments for Field Monitoring of Drilling Muds

Many types of instruments are used to measure various properties of drilling muds. The following three—Marsh-funnel viscometer, mud balance, and sieve and funnel for sand-content set—are basic instruments that one should use before and during the drilling process so that mud control can be regularly monitored during all phases of the drilling.

Viscometer

The Marsh-funnel viscometer is a funnel-shaped container, 6 in. in diameter at the top and 12 in. long. A 10-mesh screen, fitted across one-half of the top, removes foreign matter and large cuttings from the drilling mud. To determine the viscosity of a drilling mud, pour 1 qt of the drilling fluid into the funnel while holding a finger over the outlet spout. Then, simultaneously remove the finger from the



NOTE: A, B, C, D—Zones of fluid loss and eroding while drilling with water only

Figure 7.—Hole-rugosity differences caused by using improper drilling-fluid control in one of the holes.

spout and start a stop watch. When all the drilling mud has flowed out of the funnel, stop the watch and record the viscosity in seconds. Note: The Marsh-funnel viscosity of water at 70°F is 26-s; a mud viscosity of 50-s is a viscosity approximately double that of water.

Measurements obtained from the Marsh-funnel viscometer are influenced by gelation rate and density, which vary the hydrostatic head of the column of drilling mud in the funnel. An excellent, practical description of viscosity changes due to density changes, when the Marsh funnel is used, is provided in "Ground Water and Wells" (Universal Oil Products, 1966, p. 223) and is quoted in the following paragraph.

> Water shows a Marsh-funnel viscosity of 26 seconds. A good drilling mud weighing about 9 pounds per gallon usually shows a Marsh-funnel viscosity in the range of 35 to 45 seconds. If the mud picks up sand that increases its weight to 10 pounds per gallon, the Marsh-funnel viscosity may decrease to 35 seconds or less, even though its real vicosity when free of sand may be 43 seconds. The greater density of the sand-laden mud causes it to flow from the funnel faster.

In contrast, when increased mud weight is the result of picking up native clay from the ground-up cuttings, the Marsh-funnel viscosity is likely to be much higher than 43 seconds.

Mud Balance

The mud balance is a simple device that measures density of the drilling mud in pounds per gallon. The device consists of a balance beam with a fixed cup for holding a fraction of one gallon of drilling mud on one end and a sliding counterweight on the graduated arm of the balance beam. To measure the density of the drill fluid, fill the cup to capacity; seat the lid into the top of the cup, resulting in the squeezing of some mud out through the vent hole in the top of the lid; wipe off any excess mud that is on top of the lid or the sides of the cup; then move the balance rider until the instrument is balanced. Read the indicator and record the density directly in pounds per gallon. Frequent density tests will disclose any changes taking place in the unit weight of the drilling fluid.

Sand-Content Set

The sand-content set consists of a 200-mesh sieve and a graduated cone-shaped tube. To measure the sand content of the mud, pour 100 cm^3 (cubic centimeters) of drill mud onto the sieve and wash the drilling mud through the screen, using a clean-water wash. Flush the sand that is retained on the screen into the graduated cone-shaped tube and read the sand content directly in percentage by volume. Regular sand-content determinations should be performed because: (1) heavy sand content, particularly in a thin mud tends to invade aquifers resulting in a thick filter cake opposite any permeable zones, (2) heavy sand content settles out rapidly in a low gel-strength mud during drilling pauses, resulting in stuck drill pipe, and (3) excessive sand content is abrasive to pump parts and the string of drill pipe. Sand contents as high as 5 percent can be tolerated in drilling muds having proper viscosity and weight; however, when drilling in aquifer materials, sand content should be kept low.

High-Yield Bentonite Clays

High-yield bentonite clays are used to manufacture drilling muds that are high in colloidal content and gel strength. Colloids are composed of particles ranging in diameter from about 0.5 microns to 0.005 microns. Colloidal content and gel-strength properties are two extremely important components of a drilling mud. Highly colloidal clay has the ability to become hydrated with many times its own weight of water, forming a suspension that occupies a volume many times greater than that of the original solid resulting in the yield of a low-solids, high-viscosity drilling mud. It also results in a drilling mud having good filtration properties; that is, it will deposit a thin filter cake of low permeability on the wall of the hole, allowing a minimum of fluid to pass into the formation (see fig. 8 for thickness of solids and mud cake for various clays). The rapid formation of a low-permeability filter cake on the borehole wall is important whenever mud-rotary methods are used for drilling ground-water-test wells, production wells, and for coring of unconsolidated formations.

In addition to rapid filter-cake buildup properties, colloidal materials also provide a gelling function. Gel strength is that property of the drilling mud that permits drill cuttings to remain in suspension when drilling operations are halted. As long as a high gel-strength mud is in motion, it is in a viscous liquid form; however, during periods of quiescence, it becomes a semisolid. Reagitation will quickly

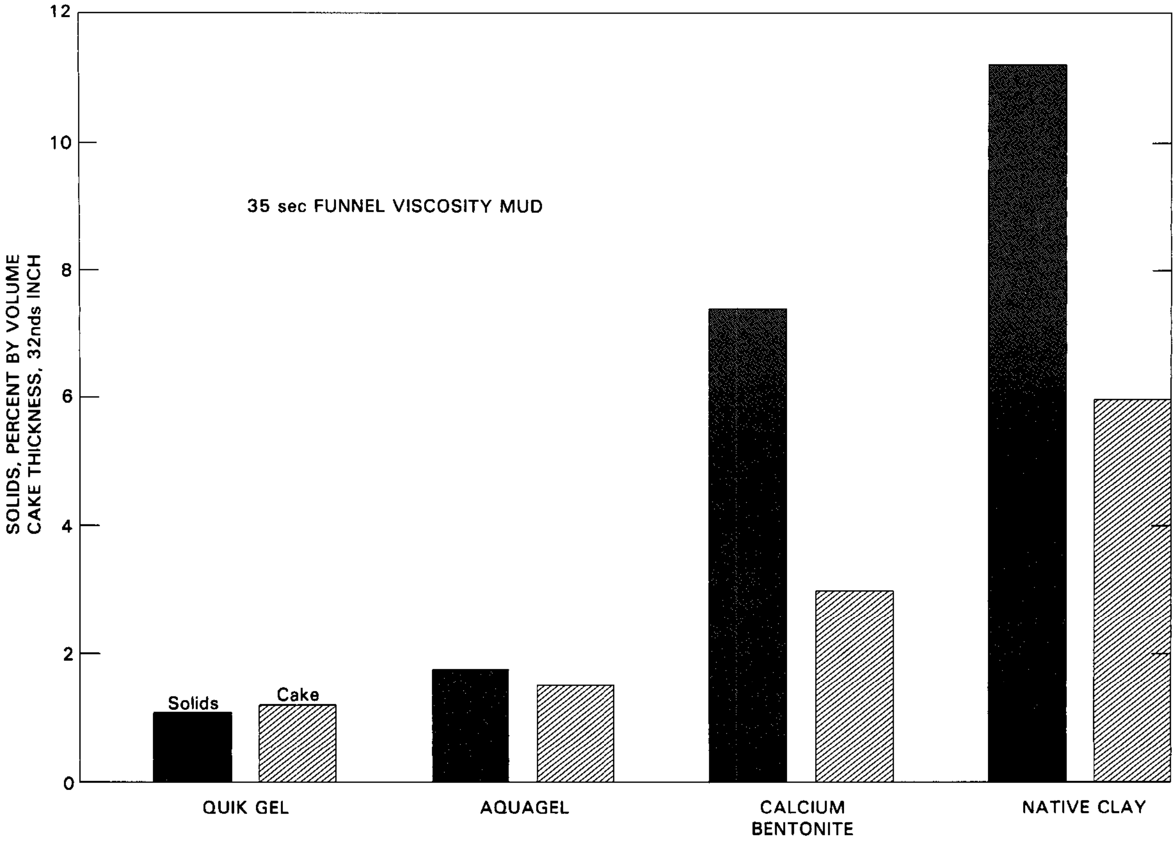


Figure 8.—Cake thickness of solids for various clays.

destroy semisolid gel and restore it to its viscous liquid form. Mixing drilling muds that have too high a gel strength can be overdone, because the mud velocity slows whenever the mud flows into the larger reservoir areas of the mud pit. When this slowing occurs the mud tends to gel, preventing the cuttings from settling out. However, some agitation of the mud in the pits by pumping and stirring can alleviate this problem.

Problems Encountered in Hydraulic-Rotary Drilling

Bit-Swabbing Damage

Surging and swabbing are methods of destroying the filter cake opposite an aquifer, allowing the aquifer materials to fall in against the screen or gravel pack. Unfortunately, they also are undesirable phenomena that occur quite frequently during the drilling process and are very harmful to the borehole. Accidental swabbing during drilling occurs because of mud-control difficulties resulting in high fluid loss opposite permeable zones, consequently causing the formation of thick filter-cake buildup opposite these permeable zones (particularly if the sand content of the mud is too high and the drill operator has failed to recognize the problem as the string of drill pipe is being removed from the hole). The density of the drilling mud will increase and the viscosity of the drilling mud will decrease as sand content increases resulting in a thicker filter cake on those sections of the hole opposite permeable zones. Whenever the drill string is removed from the hole, these less-than-bit-diameter rinds have to be removed to allow passage of the drill collars and bit. The problem begins when the drill collars and bit are pulled through the less-than-bit-diameter rind zones and a mud pack forms on the bit creating a swab or surge block. If the operator is not aware of this surging-swabbing effect, a bridged or caved hole will result. The bridging and caving of the hole occurs very rapidly, particularly if the drill string is removed from the hole very quickly or is dry. As the bit is removed from the hole at too fast a rate, the bit acts as a swabbing tool and pulls off the thick filter-cake section opposite a permeable sand (fig. 9). The forces of hydrostatic head in the formation, plus the total or partial vacuum occurring at the bottom of the bit-swab, are imparted against the momentarily resulting dewatered or negative head zone inside the hole, causing the permeable section to pump into the hole. These pumped-in cuttings either bridge or cave in the hole or settle to the bottom of it.

The hole-control-damage problem is illustrated in figure 9. How can this be prevented? Some remedial or preventive steps to alleviate the problem can be taken; however, the remedial measures require time and effort, resulting in added drilling costs. The first step is preventive and consists of close monitoring of the mud program. Proper drilling-mud control will usually prevent or minimize filter-cake buildups. However, it is not certain that smaller-diameter filter-cake rings do not exist at some points in the hole, and it must be assumed that they do.

Two methods exist for removal of the drill pipe from the hole to minimize the swabbing effect that will ruin the hole for borehole-geophysical logging and sampling techniques:

1. Remove the string of drill pipe from the hole at a relatively slow rate to minimize differences in hydrostatic head between the formation and the hole. Equalization of these pressure forces can only be accomplished if the inside of the drill string is vented to the atmosphere, allowing a completely unrestricted movement of fluid out of the pipe and bit so no changes in differential pressure occur between the fluid inside the hole and the formation. Pulling a string of drill pipe without a means for keeping the inside of the drill pipe open to the atmosphere (by using holes in the side of the pulling swivel or a regular water swivel) is referred to as dry pulling. However, if a vented string of drill pipe is pulled so fast that the mud cannot run out of the bit fast enough to keep the hole filled, bit-swabbing damage to the hole will still occur. A momentary differential pressure of a positive nature in the formation will occur (the amount of the pressure depends on the distance that the string of drill pipe is below the saturated zone), and this positive pressure will attempt to cave the hole. Never permit the drill-rig operator to repeatedly lower the string of drill pipe and run at tight spots in the hole when trying to remove the string of drill pipe because that would damage sections of the hole and would necessitate extensive flushing and redrilling to get back into the hole.

2. If borehole-geophysical logging or sampling methods are to be used that require no damage or bridging of the hole occur during removal of the string of drill pipe, the method of circulation during pulling should be used. This is a slow method, but it usually guarantees success in preventing damage to the drill hole upon removal of the string of drill pipe. Maintain circulation at a slow rate through the string of drill pipe at all times when it is being pulled. This guarantees that no great differential pressures will develop between the formation and drill hole; also, circulation will prevent buildup of muds and sands on the bit that make it act like a swab. These methods lengthen time needed to remove the string of drill pipe from the hole and may increase the cost of drilling, but the increased value of data afforded will be worth the extra effort and added cost. However, in most cases, the added time for tripping in and out of holes less than 2,000-ft depth is not a large factor in overall costs.

Borehole-Geophysical Logging

Borehole-geophysical logging is a method for continuously sampling lithologic and hydrologic parameters penetrated by the drill. The authors do not discuss any of the techniques of borehole geophysics in the manual. These techniques are fully explained in "Application of borehole geophysics to water resources investigations" (Keys and MacCary, 1971). Our reasons for mentioning borehole geophysics is that it is a very valuable sampling method and should be included in the planning stages of a drilling program; much of our discussion on mud control and hole conditioning is oriented toward conditioning the hole for gaining optimum data results from borehole-geophysical logging. In support of the need for proper mud control and hole conditioning in relationship to borehole-geophysical logging, the following is quoted from Keys and MacCary (1971, p. 20):

> Drilling a hole generally disturbs the fluids and pore spaces in the environment to be measured. Rotary drilling with mud probably causes the greatest disturbance in the environment near the borehole. In rotary drilling, a natural or artificial mud is circulated down the drill stem to bring the

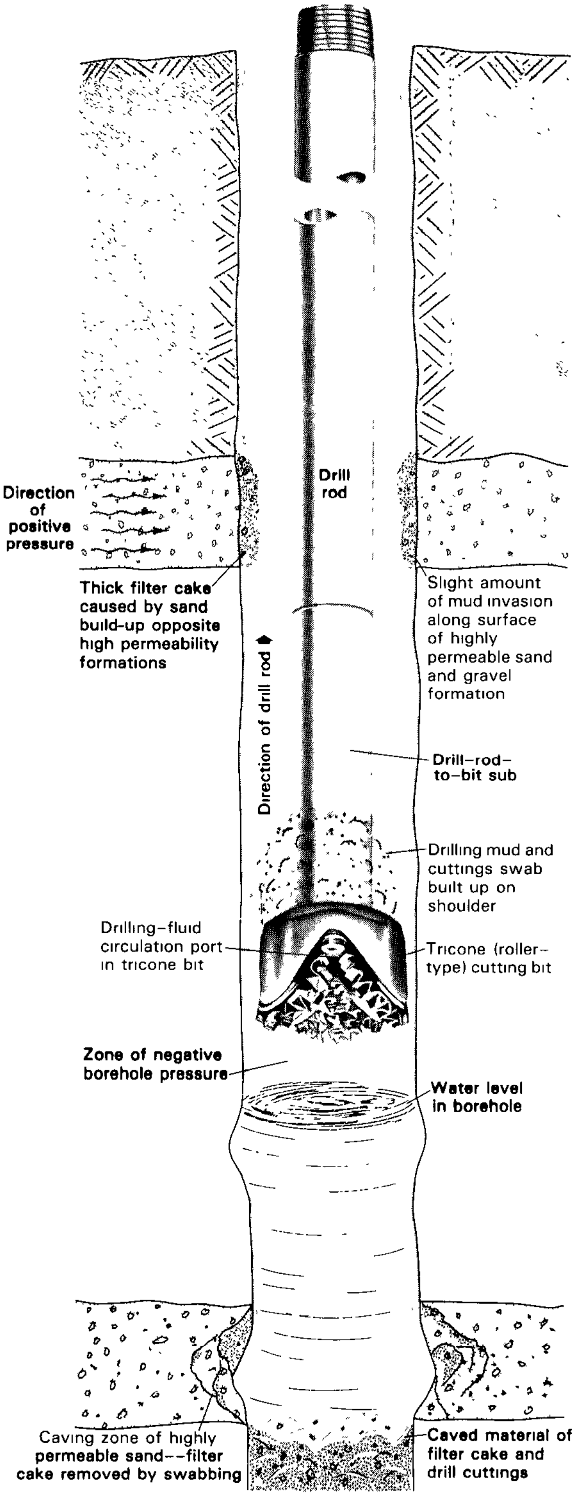


Figure 9.—Effects of bit swabbing on a borehole.

> cuttings back to the surface. The mud also keeps the hole open, cools the bit, lubricates the drill stem, coats the wall of the hole to reduce fluid loss, and serves as an electrical-coupling medium necessary for many logging operations. Because the pressure of the mud column exceeds the hydrostatic pressure in the formation being penetrated by the bit, the mud filtrate invades the rock adjacent to the borehole and displaces the native fluids away from the hole. During this process, many of the particles suspended in the mud are filtered out and form a mud cake or filter cake on the wall of the hole. The invaded zone and mud cake may introduce unknown and, in general, undesirable factors in log interpretation.
>
> The effects of drilling also have a positive aspect. Thickness of the filter cake and thickness of the invaded zone are sometimes related to the hydraulic properties of the aquifer system. In addition to the type of mud, the differential pressure, and the length of time an aquifer has been exposed to mud, the porosity and permeability of sediments will also determine the depth of invasion. In most oil fields, if all other factors are equal, the low-porosity sediments will generally be invaded deeper than the high-porosity sediments. The most obvious reason for this apparently anomalous relationship is that there is a greater volume to fill in high-porosity formations. Further, the permeability of the mud cake is generally lower than the permeability of the rock so that the mud cake and differential pressure become the factors that control the rate of filtration. In contrast, thicker invaded zones were found to occur in aquifers rather than in confining beds in shallow, poorly consolidated sediments. A complete discussion of invasion characteristics is beyond the scope of this manual, and reference should be made to Doll (1955).

Drilling and sampling operations, including good mud control, need to be designed to cause the least possible disturbance to the borehole if geophysical logging is to be done. In addition, the hole ought to be conditioned so lightweight logging tools can be lowered to the bottom of the hole. This may require complete replacement of the drilling mud that was used in the drilling process with a clean drilling mud. It may also require the method of circulating out of the drill pipe, explained on page 24 so there will be no caving or bridging of the hole as these tools are removed.

Installation of Well Casing and Screen

After the hole has been drilled to the desired depth by the hydraulic-rotary method, it is ready to be cased and screened. However, if the hole is drilled in a competent hard rock, it might be desirable to complete the well in open hole and not set casing and screen. Whatever the final method of well completion, the completed hole preparation procedures are quite similar.

When the desired hole depth has been attained, circulation of the drilling fluid is continued until all the drill cuttings have been flushed from the hole. Final flushing of the hole with a freshly prepared, low-viscosity drilling mud is advisable. By so doing, most of the fine, sand-sized cuttings still remaining in suspension in the drilling mud can be allowed to settle out in the mud-circulation pit instead of settling to the bottom of the hole.

After the hole has been flushed, the drill pipe is removed using either of the methods previously discussed to prevent bit-swabbing hole damage. The well screen and casing are then set and sealed in the clean, drilling-fluid filled hole; the drilling fluid is pumped out, and the well is developed using the appropriate well-development techniques.

Cable-Tool Percussion Drilling

The cable-tool percussion method of drilling is one of the oldest drilling methods known. Its first recorded use was in China about 600 B.C. for percussion drilling of relatively shallow brine wells. Cable-tool percussion drilling is still a very versatile tool for obtaining good subsurface geohydrologic data when used for test-hole drilling; and this method probably is used to install more water wells than any other method. Although the Water Resources Division, U.S. Geological Survey, does not own or operate any cable-tool rigs they are used extensively in contracting for relatively shallow test holes in both hard rock and unconsolidated formations. A very brief and basic description of the method is given, and some methods for taking cores in cable-tool drilled wells is presented in this manual to provide the hydrologist with more than just cutting samples from the hole. Many articles describe the cable-tool method in detail; we refer those readers who plan to use the method for contract-test drilling to two specific references: "Ground Water and Wells" (Universal Oil Products, 1966, chap. 11) and "Water Well Technology" (Campbell and Lehr, 1973, chap. 4).

Applications of Cable-Tool Percussion Drilling

Drilling test holes and water wells by the cable-tool method is an old and reliable method. Cuttings returned by the bailer and evaluated in conjunction with a competent cable-tool driller's log provide a good description of the drilled lithologic materials. This method, used also in conjunction with drive-core samples, can provide accurate subsurface information. Collecting water samples from a cable-tool drilled hole when using the drive-casing mode is unsurpassed. Unfortunately, specifications are usually not written adequately to ensure that the maximum data are obtained from a cable-tool drilled hole. For instance, specifications might be written that do not call for drive-core sampling, thin-walled Shelby-tube sampling, or even a collection of water samples from the aquifers drilled. These data are relatively easy to obtain in the process of the drilling in drive-casing method of cable-tool drilling, but they are impossible to obtain after the well has been completed. Also, various geophysical-logging methods are available that can provide information on water quality in an uncased hole, but none exist that can provide data or water quality once the casing has been installed. Only radiation-type logging devices can be used in a cased well; for instance, the natural gamma log can provide information on grain-size distribution. The quality of data and types of data needed and the method by which these data are to be obtained should be carefully considered prior to writing the final contract of drilling specifications.

Also, in writing specifications, do not restrict the drilling contractor. A set of recently reviewed specifications specified that "a cable-tool hole be drilled and a 6-in. casing driven to a depth of 725 ft, a 20-ft length, 4-in.-diameter screen installed using the casing pull-back and swedging method." The restrictive aspect of this specification was that the drilling contractor would have to accomplish this by using a single string of 6-in.-diameter casing; no telescoping of casing was allowed. Ultimately, the skin friction on the outside of the 6-in. casing would become so great that it could not be driven to the specified depth of 725 ft but would break in the attempt. Drilling and driving a specified diameter casing to a given depth is done by starting out with a larger casing (12-in.) and going with it to refusal; then reducing to 10-in.-diameter casing, and drilling and driving it to refusal. This telescoping of casing is continued as a method for reaching final depth at the specified diameter. The writer of drilling specifications should contact drilling contractors in the area of interest for professional input on local conditions to complete a well in that area.

Equipment and Accessories

A complete string of drilling tools for cable-tool drilling consists of a set of rope sockets, set of drill jars, a drill stem (for added weight), and a drill bit. The drill jars have no function in the initial drilling process; they are included in the drilling tools as a precautionary measure and would be used under the following problem conditions:

1. If drilling was performed in an uncased hard-rock hole, and vibration resulting from the bit striking the bottom of the hole caused a piece of rock to fall out of the wall of the hole on top of the drill bit, it might be impossible to pull the drill bit out of the hole with the wireline hoist. If this occurs, the drill cable would be slacked off to allow the jar links to open to their full length. Then, on the upstroke, the jars would impart a blow to the tools below. Repeating this jarring procedure would break the rock that had fallen in on top of the drill bit, thereby freeing the drilling tools and drill bit.

2. When drilling in unconsolidated materials using the cable-tool method, it is common practice to drill ahead of the casing a few feet to facilitate later driving of the casing. Occasionally, when this method is used, gravel or boulders will fall in and lock up the bit; here, the jars would be used as described above to obtain the same results.

Methods of Drilling

The cable-tool drilling method is relatively simple; the drilling-tool string is alternately raised and dropped through the use of a spudding arm, with the drill string suspended by left-lay drill cable. Drilling is accomplished without letting the cable go completely slack when the bit strikes bottom, maintaining some pull and stretch on the cable. The elasticity and lay of the cable permits, through the cable swivel, a few degrees turn of the bit each time the drilling tool string is raised and lowered, allowing the cutting section of the bit to strike a new section of the hole on each drop. Turning the bit is necessary if a round hole is to result; otherwise the well would be concave-oval shaped like the bit. In drilling practice by the cable-tool method, water, sometimes with mud added, is poured into the hole, so that the cuttings generated by the action of the bit can form a slurry and remain in suspension, allowing the bit to strike undrilled rock instead of material that has already been cut. These slurried cuttings periodically have to be bailed out of the hole; otherwise their viscous nature restricts the free fall of the drilling-tool string, resulting in a slower penetration rate.

If cable-tool drilling is performed in competent rock, no casing is used in the drilling operation, because the hole wall will not collapse and cave in. However, when cable-tool drilling is performed in unconsolidated formations, casing has to be driven to support the hole wall and prevent caving. The basic procedure for drilling and driving casing in unconsolidated material follows:

A section of heavy-wall drive casing is equipped with a sharpened cutting shoe and is driven to the bottom of the hole (the cutting shoe will have to shave off a section of the wall). The bit assembly is then run to the bottom of the hole, water is poured in, and the drilling is resumed. After the hole has been drilled to about 5 ft below the casing (depth will usually depend on the driller's assessment of the competency of the material), the bit assembly is removed from the hole, the slurried cuttings are bailed out, the drive clamps are reattached to the drill stem, and the casing is once again driven to the bottom of the hole. In very soft formations, the driller may drive the casing beyond the point at which the hole has been drilled, water can be poured in the casing to form a slurry with the drilled cuttings, and the material can be bailed out. This procedure of drilling, bailing, and driving the casing can continue to considerable depth. After the water table has been reached, it is usually no longer necessary to add water for creating slurry.

Installation of Well Casing and Screen

There are so many different ways of installing well screens by using the cable-tool method (that is, casing pulled back, bailed down, wash-in, etc.) that they will not be described in this manual. For excellent examples and descriptions of the methods, the reader is referred to "Ground Water and Wells" (Universal Oil Products, 1966) and "Water Well Technology" (Campbell and Lehr, 1973).

Air-Rotary Drilling

Air-rotary drilling has become an increasingly popular method for drilling test holes and wells. Air was first used as a drilling circulating medium as early as the late 1800's. Extensive test drilling for uranium during the 1950's caused the air-rotary drilling industry to gain considerable momentum in the drilling field. It was not without its problems, however, and the high cost of compressors made the method too prohibitive for use by many drilling contractors. As more research was conducted in the field of air-rotary drilling and greater capacity air compressors were developed, the method became economically more feasible.

Applications of Air-Rotary Drilling

The air-rotary method of drilling is a particularly effective method to use when drilling hard rock. Penetration rates are generally faster and drilling costs lower than using other conventional drilling methods for drilling these materials. Bottom-hole percussion tools and bits are most often used for this purpose.

Air-rotary drilling is often preferred over hydraulic-rotary methods for drilling wells in highly fractured and cavernous rock aquifers where the loss of costly drilling fluids is a problem. However, this type of drilling environment requires large volume compressors and drilling foam to remove the cuttings from the hole and accomplish the drilling. The drilling additives used in air-rotary drilling to prevent lost circulation in the rock are not usually as detrimental through plugging of the aquifer as many other conventional hydraulic-rotary drilling muds.

Equipment and Accessories

The basic air-rotary drilling rig is equipped essentially like a drilling rig used for conducting hydraulic-rotary drilling, with the major exception being that the standard mud pump is replaced by a compressor and compressor-cooling assembly. An air-rotary drilling rig is also equipped with a fluid-injection pump that is capable of delivering fluid volumes ranging between about 6 and 20 gal/min. Like a mud-rotary drilling rig, an air-rotary drilling rig has a derrick and hoist, a pull-down and hold-back system, and a revolving rotary table and kelly system to turn the drill pipe. The drilling-tool string consists of sections of drill pipe, drill collars to provide weight and stability to the string of drill pipe, and a cutting tool or bit that is attached to the bottom end of the string of drill pipe and collars. The entire system is engine powered.

Methods of Drilling

The methods of drilling with air are basically the same as those methods used for hydraulic-rotary drilling. Air is used instead of a drilling mud as the circulating medium to cool the bit and remove the bit-drilled cuttings from the hole. The injection pump is used in conjunction with the air compressor to aid in the removal of sticky, wet cuttings from the hole; otherwise they tend to accumulate on the drill pipe and also plug the bit. Drilling foam, polymers, and other drilling additives can be mixed with the injection fluid to stabilize the hole wall and aid in the removal of drilled cuttings from the hole.

The minimum annular air velocity required to adequately clean the cuttings from a hole (drilling with dry air) is about 3,000 ft/min. The annular velocity of air can be calculated as follows:

$$AV = \frac{\text{cfm} \times 144 \text{ in.}^2/\text{ft}}{\text{area of annulus (in.}^2)}$$

where AV = annular velocity,
cfm = cubic feet of free air per minute.

If drilling foam or other gel additives are injected considerably lower air velocity and annular pressure are required to lift the cuttings from the hole. For a more detailed overview of the air-rotary drilling method, see "Water Well Technology" (Campbell and Lehr, 1973, p. 121–136).

Borehole-Geophysical Logging

If the hole is to be geophysically logged upon completion of drilling, it must be properly conditioned beforehand. Regardless of the drilling methods or type of drill used to make the hole the criteria necessary for conditioning the hole prior to logging are basically the same. The drilled cuttings have to be removed and the hole wall stabilized to prevent caving or bridging if open-hole logs are to be run in the borehole before casing is set. Borehole swabbing can also occur in an air-rotary-drilled hole because of mud buildup formed on the bit and the formation of mud rings on the drill pipe. Therefore, when the drill pipe is removed from the hole to facilitate logging, it should be done with care.

Installation of Well Casing and Screen

The borehole is first flushed of all drilled cuttings. This can be accomplished by circulating air, air mist, foam, and (or) polymers in the hole until it is clean and no bridging or caving occurs. The drill pipe is then carefully removed from the borehole and the casing and screen are set in the open hole and sealed in place. After the installation is completed, the well is developed as necessary.

Reverse-Circulation Drilling

The method of reverse-circulation drilling was designed primarily for drilling large-diameter production wells in unconsolidated formations. The practical minimum diameter (about 16 in.) for drilling holes by the reverse-circulation method almost precludes its being used for test-hole drilling. However, this method provides the best cuttings samples of any drilling method because of the large intake capacity of the bit (5 in. or more); this method also provides fast delivery of cuttings to the surface because of high ascending velocities (can be several hundred feet per minute) of the drill cuttings and fluid. Therefore, reverse circulation is an excellent drilling method for obtaining cutting samples. For those readers interested in the method, comprehensive descriptions are provided in "Water Well Techology" (Campbell and Lehr, 1973) and "Ground Water and Wells" (Universal Oil Products, 1966).

TECHNIQUES FOR CORING

Hydraulic-Rotary Coring

Hydraulic-rotary coring is commonly referred to as diamond drilling. The name seems to fascinate people, possibly because it was originally used to explore for gold and other valuable minerals. Even today, when coring is used to collect samples for many reasons, this fascination with coring still exists. Coring is the one method of drilling that extracts from the earth an actual piece of the earth that the hydrologist, geologist, engineer, or other scientist can feel, see, and study in great detail.

Hydraulic-rotary coring as a drilling method has existed for over 100 years; during that relatively short period of time, the equipment and techniques for obtaining good core quality and recovery, particularly in hard rock, have advanced dramatically, although the basic method has changed little.

Some of the basic techniques involved in hydraulic-rotary coring parallels the techniques of hydraulic-rotary drilling. A drilling fluid is circulated to carry cuttings out of the hole, cool the bit, lubricate the rotating drill pipe, and so forth. Some major components used in hydraulic-rotary coring, such as drilling rigs and mud pumps, may be identical to those used for hydraulic-rotary drilling. However, for most coring operations, equipment can vary considerably; see figure 10 for a typical hydraulic-rotary coring rig and associated equipment. Hydraulic-rotary coring does not require the amount of rig power that is needed for standard hydraulic-rotary drilling, nor does it require a large drilling-fluid circulation pump because much less volume of drilling fluid is needed in coring operations. Drill bits used for hydraulic-rotary drilling also vary considerably from those used in hydraulic-rotary coring. Drill bits used for hydraulic-rotary drilling are designed to cut away all material that is penetrated, whereas the coring bit is designed to cut the perimeter of penetrated materials and allow the central material to remain intact and enter the core barrel.

In the next sections, a detailed description of the problems encountered and techniques used in the hydraulic-rotary coring of unconsolidated formations is discussed because this is the type of material that is most often involved with ground-water studies; most difficulties in obtaining hydraulic-rotary cores also are presented. No detailed description of diamond grades, carat weights, setting of diamonds, etc., is provided. If the reader wants information concerning these subjects, see publications from the many manufacturers of diamond-drilling products, some of which are included in the list of references. This subject is treated in detail in “Diamond Drill Handbook” (Cumming, 1969).

Equipment and Accessories

Before discussing methods of hydraulic-rotary coring, some information on equipment sizes is necessary. For years, the nomenclature used in describing various component parts of hydraulic-rotary coring equipment has been difficult to understand. For example, the sizes designated—EX, AX, BX, NX, and HX for bits, reaming shells, core barrels, and flush-coupled casing; E–EW, A–AW, B–BW, N–NW, and H–HW sizes designated for drill rod—are difficult to understand. Because these size designations were not systematic, they could not be retained in the mind of the casual user. In addition, each manufacturer has its own thread design for many of the various components, which further complicated the situation and confused even drill crews. As an example, a drill crew might be beginning a job that requires setting a few hundred feet of flush-joint NX casing through overburden and obtaining core using an NX-core barrel to a depth of 1,000 ft. Very likely, the drill crew might not have enough of one manufacturer’s type of casing to completely case out the overburden and would have to use two or three different manufacturer’s casing, all with different threads. In addition, the drill crew might have to use drill-rod diameters made by various manufacturers to core the total depth. Coupling the different diameter drill rods requires a crossover sub for each thread change, amounting to as many as six or eight subs and much time loss and extra expense.

Problems resulted from the past lack of hydraulic-rotary coring equipment size standards, and much of this mismatched equipment is still in use today and will continue to be in use. Fortunately, over a period of years, core-drill manufacturers, and users of the equipment, recognized the need for established standards in the United States and other countries, and they developed standards for the inhole components for diamond drilling. These are known as DCDMA (Diamond Core Drill Manufacturers Association) standards and were adopted by the industry in 1970 (fig. 11). Unfortunately, standards have not as yet been adopted for wire-line core barrels. However, where

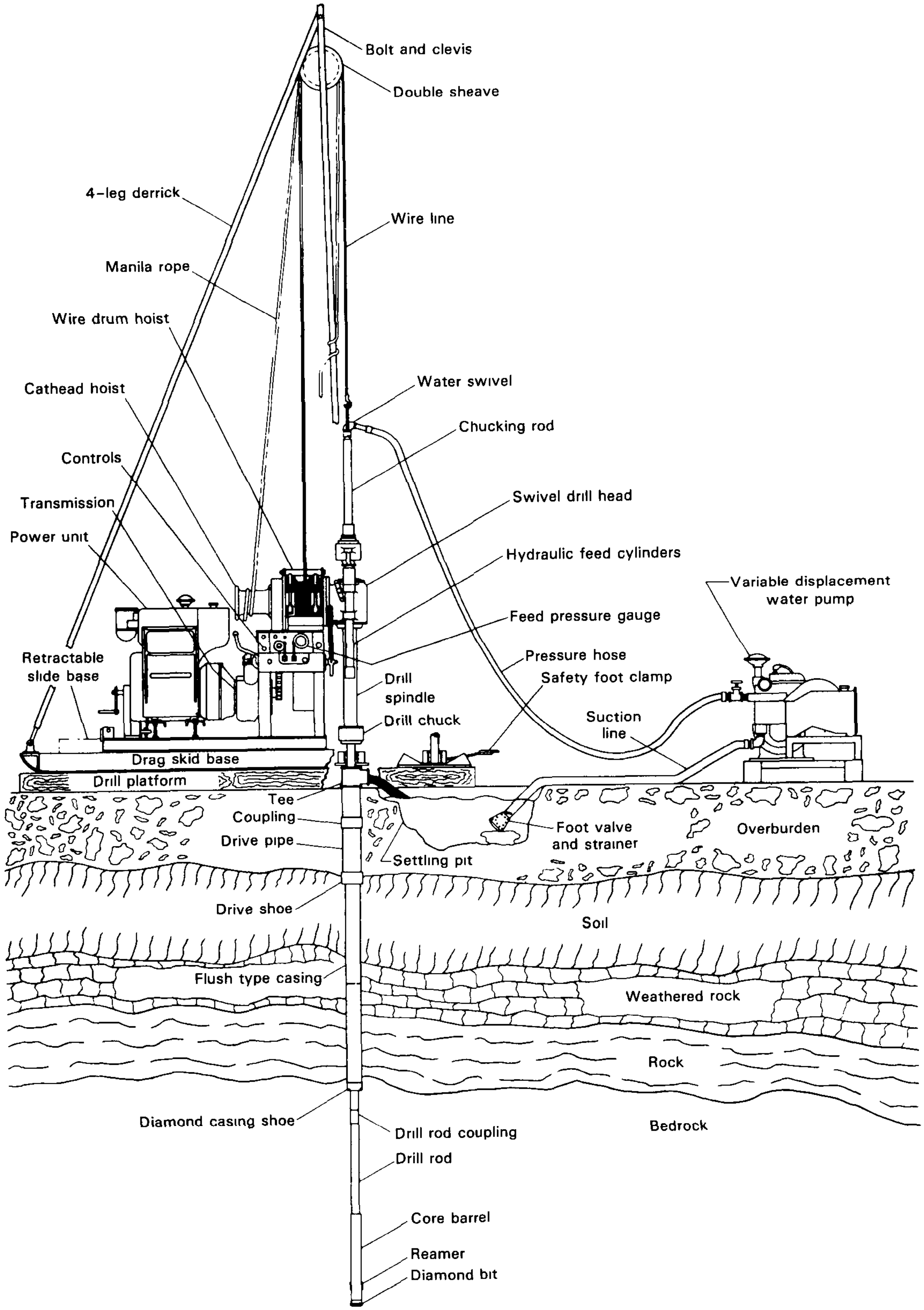


Figure 10.—Typical diamond-drilling rig for exploration (Acker, 1974, reprinted by permission from Acker Drill Co., Inc.).

standards do exist they should be used whenever a written drilling and coring specification contract is prepared.

Much of the equipment used for hydraulic-rotary coring of unconsolidated materials is the same as that used for hydraulic-rotary coring of rock. The core-drilling rig, drilling-mud mixing equipment, and drilling-fluid circulating pump may be the same. However, the smaller duplex pumps ordinarily used to circulate the drilling fluid for rock coring operations cannot be used for circulating the high-viscosity muds for coring unconsolidated materials. Most of the combination auger-drilling and hydraulic-rotary drilling rigs that are used by the USGS Water Resources Division for drilling and coring are equipped with positive displacement, rotor-stator pumps that can readily circulate drilling muds having high viscosities. Drill pipe and core barrels can be the same; however, use of wireline-core barrel systems insure greater hole stability while drilling and coring. The wireline-core barrel consists of an outer tube equipped with a diamond-set reaming shell and core bit at the lower end, a retrievable locking inner-barrel assembly equipped with a core retainer at the lower end, a swivel-type ball-bearing head at the upper end of the inner barrel, and a locking head and spear above the ball-bearing swivel assembly. Cutting bits used for coring unconsolidated material are different from those used for coring rock. Most rock-coring bits allow passage of the drilling fluid through the annulus between the core barrel, outer tube, and inner barrel, through the cutting edge of the bit (in direct contact with the core); and referred to as face-discharge diamond-core bits (fig. 12). These bits cannot be used to core unconsolidated or extremely friable formations because of the eroding action of the drilling fluid as it discharges directly on the core. Bits used for coring unconsolidated or friable formations (fig. 13) are of the recessed, bottom-discharge types, and because of the recessed waterway the drilling fluid does not come in contact with the core, thereby practically eliminating core-erosion problems.

The recessed-bottom-discharge bits provide another feature to help eliminate core erosion. As the drill pipe rotates, the fluid tends to be thrown outward, not downward, thereby preventing washing and contamination of the core; however, this feature is more costly to the life of the diamond-coring bit because little fluid gets to the inside cutting edge of the bit, resulting in excessive diamond wear of that section of the bit. When a bottom-discharge diamond-coring bit is used, adjustment of the inner barrel is very important. The core barrel is taken apart and a skirted, special-length, pilot core-retainer inner-tube shoe (fig. 13) is attached to the end of the inner barrel. The inner barrel must be adjusted to fit closely to the bottom of the cutting bit so the drilling fluid will be directed out through the recessed ports and not out through the face of the bit. This inner-tube adjustment is made by loosening the holding nut on the inner-barrel spindle assembly (threaded rod) and turning the threaded spindle rod into or out of the swivel assembly. The amount of adjustment is made by trial and error; the adjustment, reassembly, disassembly, and adjustment may have to be done several times to accomplish the proper clearance (about 1/16 of one inch) to avoid slack in the bearings, particularly after use. To check the inner tube for proper clearance, the assembled barrel is placed horizontally and the inner tube is pushed up. The core will force the inner tube up to this position when coring is being done. The inner tube should not rest tightly against the cutting-bit shoulder, or the inner tube will turn with the outer barrel. After proper adjustment of the inner tube, the spindle nut must be retightened so the adjustment cannot change during coring operations.

Methods of Coring

Coring Procedures in Unconsolidated Sediments

Hydraulic-rotary coring of unconsolidated sediments for the purpose of obtaining undisturbed cores is extremely difficult, compared to hydraulic-rotary coring of rock. Most core drillers consider it impossible to core unconsolidated materials and, as a consequence, many will not attempt it. These unconsolidated materials are most commonly referred to as overburden and they are cased off in the exploration-drilling industry, prior to starting any coring operations. However, the overburden is usually of major interest in water-resource investigations.

The USGS Water Resources Division has funded research to look into methods and techniques for coring and sampling unconsolidated formations, particularly aquifer materials. These research

D.C.D.M.A. STANDARD SIZES (NOMINAL)

DRILL RODS & COUPLING

SIZE	OD		ID		THREADS	WGT		COUPLING-ID	
	IN.	MM	IN.	MM	PER IN.	LBS/FT.	KG/M	IN.	MM
*RW	1-3/32	27.8	23/32	18.3	4	1.95	2.90	13/32	10.3
*EW	1-3/8	34.9	15/16	23.8	3	3.1	4.6	7/16	11.1
*AW	1-3/4	44.4	1-1/4	31.8	3	4.2	6.25	5/8	15.9
BW	2-1/8	54.0	1-3/4	44.5	3	4.3	6.4	3/4	19.0
NW	2-5/8	66.7	2-1/4	57.1	3	5.5	8.18	1-3/8	34.9
HW	3-1/2	88.9	3-1/16	77.8	3	7.73	11.5	2-3/8	60.3
*E	1-5/16	33.3	7/8	22.2	3	2.7	4.02	7/16	11.1
*A	1-5/8	41.3	1-1/8	28.6	3	3.7	5.51	9/16	14.3
*B	1-7/8	47.6	1-1/4	31.7	5	5.0	7.44	5/8	15.9
N	2-3/8	60.3	2	50.8	4	5.2	7.74	1	25.4

ROD LENGTH IS 2', 5' OR 10'

* PARALLEL WALL

"X" SERIES FLUSH COUPLED CASING

SIZE	OD		ID		THREADS	WGT.		COUPLING-ID	
	IN.	MM	IN.	MM	PER IN.	LBS/FT.	KG/M	IN.	MM
RX	1-7/16	36.5	1-3/16	30.2	8	1.75	2.6	1-3/16	30.2
EX	1-13/16	46.0	1-5/8	41.3	8	1.80	2.68	1-1/2	38.1
AX	2-1/4	57.2	2	50.8	8	2.90	4.32	1-29/32	48.4
BX	2-7/8	73.0	2-9/16	65.1	8	4.53	6.75	2-3/8	60.3
NX	3-1/2	88.9	3-3/16	81.0	8	5.57	8.28	3	76.2
HX	4-1/2	114.3	4-1/8	104.8	5	8.65	12.87	3-15/16	100.0

"W" SERIES FLUSH JOINT CASING

SIZE	OD		ID		THREADS	WGT.	
	IN.	MM	IN.	MM	PER IN.	LBS/FT.	KG/M
RW	1-7/16	36.5	1-3/16	30.2	5	1.75	2.6
EW	1-13/16	46.0	1-1/2	38.1	4	2.76	4.11
AW	2-1/4	57.2	1-29/32	48.4	4	3.80	5.65
BW	2-7/8	73.0	2-3/8	60.3	4	7.00	10.42
NW	3-1/2	88.9	3	76.2	4	8.69	12.93
HW	4-1/2	114.3	4	101.6	4	11.35	16.89
PW	5-1/2	139.7	5	127.0	3	15.35	22.84
SW	6-5/8	168.3	6	152.4	3	19.49	29.0
UW	7-5/8	193.7	7	177.8	2	23.47	34.92
ZW	8-5/8	219.1	8	203.2	2	27.80	41.36

CASING LENGTH IS 2', 5' OR 10'

MINIMUM PHYSICAL MATERIAL STRENGTH	YIELD	TENSILE
PARALLEL WALL DRILL ROD	65,000 PSI	80,000 PSI
UPSET OR FORGED END DRILL ROD	40,000 PSI	60,000 PSI
CASING	65,000 PSI	80,000 PSI

"W" GROUP CORE BARRELS

"G" DESIGN SIZE OD		CORE DIAMETER	"M" DESIGN SIZE OD		CORE DIAMETER	"T" DESIGN SIZE OD		CORE DIAMETER
	IN.	IN.		IN.	IN.		IN.	IN.
EWG	1-1/2	7/8	EWM	1-1/2	7/8	EWT	1-1/2	29/32
AWG	1-7/8	1-1/8	AWM	1-7/8	1-1/8	AWT	1-7/8	1-9/32
BWG	2-3/8	1-5/8	BWM	2-3/8	1-5/8	BWT	2-3/8	1-3/4
NWG	2-15/16	2-1/8	NWM	2-15/16	2-1/8	NWT	2-15/16	2-5/16

LARGE DESIGN CORE BARRELS

SIZE	OD	CORE DIAMETER
	IN.	IN.
2-3/4 x 3-7/8	3-7/8	2-11/16
4 x 5-1/2	5-1/2	3-15/16
6 x 7-3/4	7-3/4	5-15/16

DIAMOND CORE BITS

SIZE	HOLE DIAM	CORE DIAM	SET DIMENSIONS (INCHES ± .005)	
	IN	IN	OD	ID
EWG-EWM	1-1/2	7/8	1.470	.845
AWG-AWM	1-7/8	1-1/8	1.875	1.185
BWG-BWM	2-3/8	1-5/8	2.345	1.655
NWG-HWM	3	2-1/8	2.965	2.155
HWG	3-7/8	3	3.890 (± .0075)	3.000

DIAMOND CASING BITS & CASING SHOE BITS

	SET DIMENSIONS (INCHES ± .005)			
	CASING	BITS	CASING SHOE BITS	
SIZE	OD	ID	OD	ID
EW-EX	1.875	1.405	1.875	1.494
AW-AX	2.345	1.780	2.345	1.899
BW-BX	2.965	2.215	2.965	2.370
NW-NX	3.615	2.840	3.615	2.992
HW-HX	4.625 (± .0075)	3.777	4.625 (± .0075)	3.925

NOT DCDMA STANDARD FOR REFERENCE ONLY

LONGYEAR Q SERIES WIRE LINE (NOMINAL SIZES-INCHES)

SIZE	DRILL RODS		OUTER TUBE		INNER TUBE		CORE BARRELS HOLE	CORE
	OD	ID	OD	ID			DIAM	DIAM
AQ	1-3/4	1-3/8	1-13/16	1-7/16	1-9/32	1-1/8	1-57/64	1-1/16
BQ	2-3/16	1-13/16	2-1/4	1-13/16	1-11/16	1-1/2	2-23/64	1-7/16
NQ	2-3/4	2-3/8	2-7/8	2-3/8	2-3/16	1-31/32	2-63/64	1-7/8
HQ	3-1/2	3-1/16	3-5/8	3-1/16	2-7/8	2-5/8	3-25/32	2-1/2

Figure 11.—Diamond Core Drill Manufacturers Association standards for casing, drill rods, core barrels, and diamond bit dimensions (Acker, 1974, reprinted by permission from Acker Drill Co., Inc.).

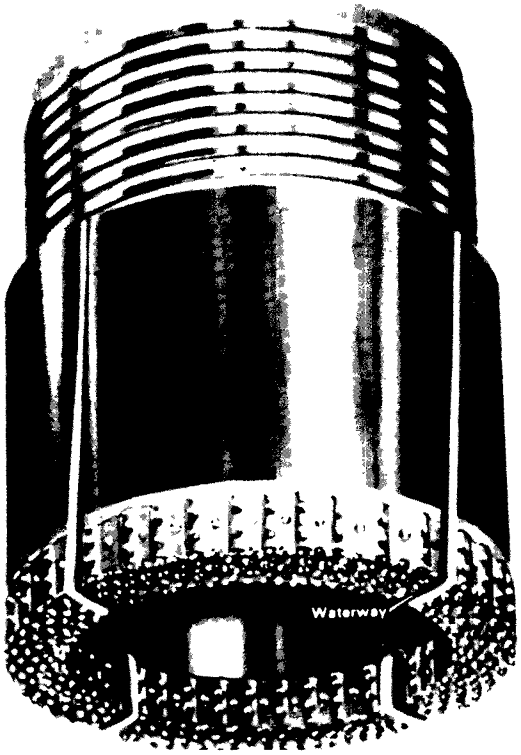


Figure 12.—Face-discharge diamond-core bit.

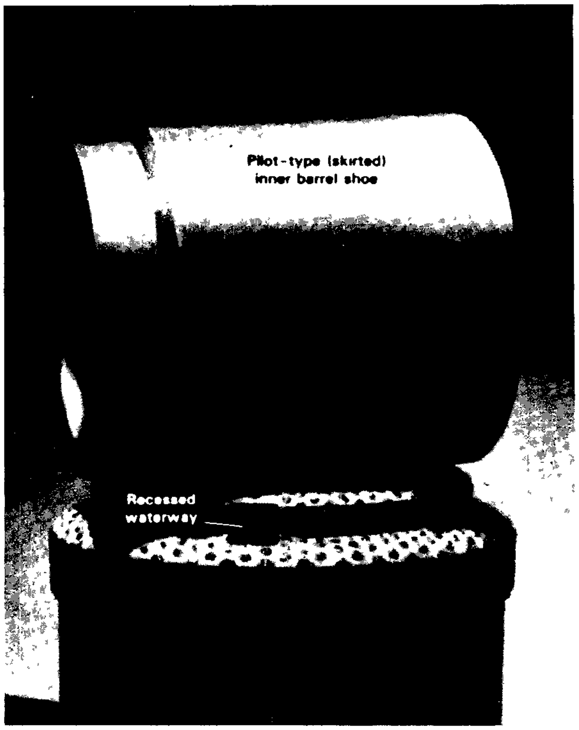


Figure 13.—Recessed bottom-discharge-type diamond-coring bit and pilot inner-barrel shoe.

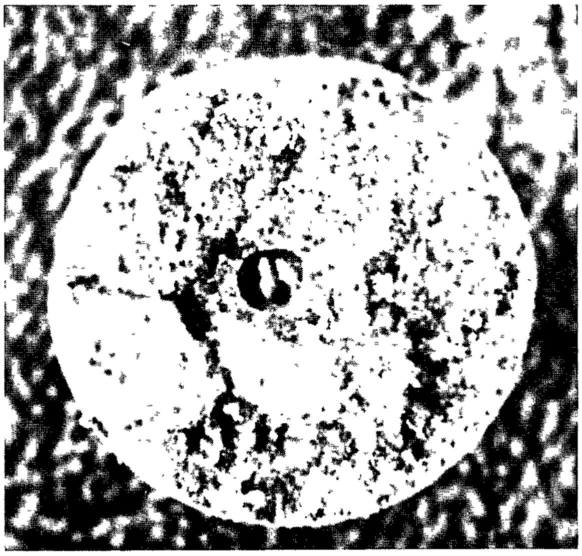


Figure 14.—Hydraulic-rotary core of unconsolidated, fine-grained Ogallala sand.

efforts have shown that: (1) most unconsolidated materials can be cored by the hydraulic-rotary method and (2) hydraulic-rotary coring is a slow and expensive process requiring a considerable amount of operator patience and expertise. All sands, silts, clays, and combinations of these materials can be cored by the hydraulic-rotary method with very little disturbance or contamination, if the proper techniques are used. Certain materials, such as boulders, and gravels having no matrix of sand-silt-clay to hold them in place, can possibly be cored, but the core is badly disturbed and contaminated by invasion of drilling fluid. The methods and techniques that the USGS Water Resources Division uses to core unconsolidated sediments are shown in figures 14 through 16 which are photographs of hydraulic-rotary cores of unconsolidated and loosely consolidated sediments.

For example, assume a short section of surface casing has been installed to prevent erosion or cratering around the borehole at ground surface, the top several feet of the formation are top soil (loam, silt, sand, clay mixture), and 50-s viscosity mud has been prepared. After attaching a 5-ft long HQ core barrel (no longer core barrel should be used in coring unconsolidated materials) to the spindle rod or fluted kelly and setting the coring bit in the

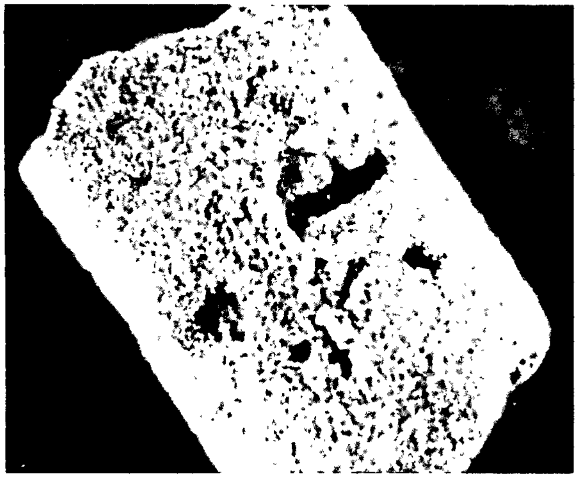


Figure 15.—Hydraulic-rotary core of loosely consolidated Ogallala sand with solution openings.

surface casing, circulate the drilling mud at a rate of about 10 gal/min. Note that the circulation of this amount of viscous drilling mud through the coring bit ports results in a fluid pressure of about 25 lb/in.^{2} as shown on the pressure gage. Rotate the core barrel at about 50 r/min while, at the same time, applying a low down pressure not to exceed 50 lb/in.^{2} The down pressure applied should be only enough to penetrate the material at a rate of about 1 ft every 5 min. The core must be cut and not pushed into the core barrel. As the core is being cut, the fluid pressure increases to 35–50 lb/in.^{2} as a result of the drill mud forcing the cuttings up a restricted annulus. However, if the fluid pressure climbs very rapidly, then the penetration rate is too fast. The pressure buildup is caused by: (1) collecting of too many cuttings in the hole, or (2) plugging of the coring-bit discharge ports. If the penetration rate is not reduced at this point, deep drilling-fluid contamination of the core or complete plugging of the coring bit will occur. After the core barrel is seated in, assuming the drill pipe is rotating true (no wobble or vibration) in the hole, the rotational speed can be increased above the recommended 50 r/min used for starting the coring operation. However, high rotational speeds used for coring hard rock cannot be employed for coring fragile, unconsolidated material. With the exception of coring in clay, rotational speed of the coring bit should not exceed 250 r/min. After the 5 ft of core has been taken, the core barrel is removed from the hole, the core taken out of the inner barrel, and the core barrel is returned to the bottom of the hole for the continuation of coring.

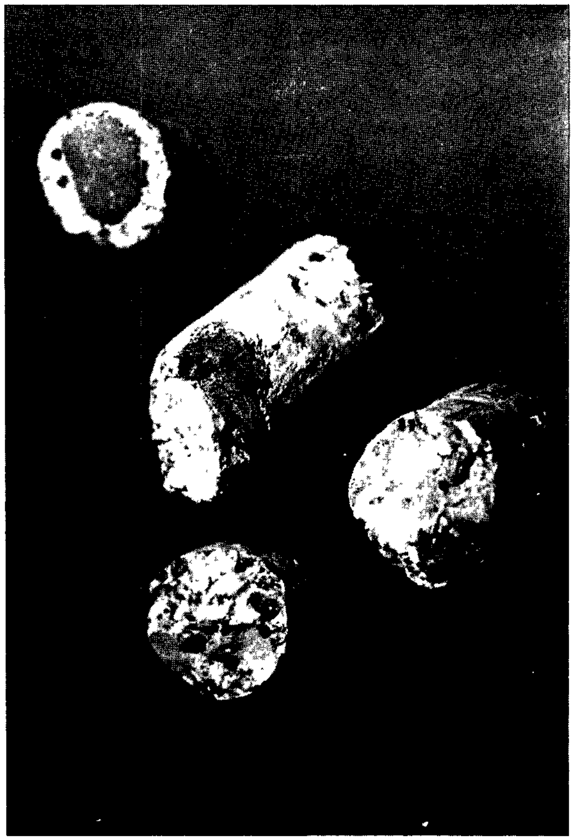


Figure 16.—Hydraulic-rotary core of loosely consolidated gravels in a matrix of silty sand.

A more detailed explanation of penetration rate follows: In unconsolidated materials, considerable density-hardness differences occur as lithologies change downhole; partially indurated zones may be encountered that are directly underlain by very soft and uncemented materials. These density-hardness changes are one of the most troublesome aspects when trying to core unconsolidated materials by the hydraulic-rotary method and probably account for the reason that many core drillers do not attempt coring of unconsolidated materials by this method. For example, assume a low-density material is being cored by the hydraulic-rotary method. The coring progresses satisfactorily, using 25 lb/in.^{2} down pressure on the bit until a high-density cemented material is encountered and, obviously from observing the spindle chuck or hydraulic traveling table, penetration stops. Penetration is resumed by increasing the weight on the bit by adjusting the hydraulic downfeed valve until the bit pressure is about 200 lb/in^2. Further, assume that, after the cemented zones have been cored, for 1 or 2 ft the bit suddenly breaks through the hard zone into a very soft formation. The 200 lb/in.^{2} down pressure on the bit that was required to core the hard zone at a rate of 1 ft/5 min now pushes it into the softer formation at a rate of about 20 ft/min, causing complete blockage of the bit and bit ports. The only solution is to trip out of the hole and unplug the bit. The only way to prevent this situation from occurring is to pay strict attention to the variations in bit pressure and drilling-fluid pressure as coring progresses, and as soon as the coring bit breaks through the hard material the bit downfeed pressure needs to be decreased immediately.

Some core drills are equipped with a detent valve which through manipulation allows the downfeed rate to be set at a predetermined speed regardless of the weight or down pressure acting on the coring bit. This prevents fast penetration and resultant bit plugging when breakthrough of the hard material occurs. This detent device should be considered whenever hydraulic-rotary coring in unconsolidated materials is done. The same type of safety feature is accomplished by experienced drillers using standard coring machines who partially set the brake on the planetary winch and make the hydraulic downfeed overcome the applied braking holdback.

To further discuss hydraulic-rotary coring of unconsolidated materials, look at deeper coring of various lithologic units. Assume that at a depth of 100 ft, a medium sand with a fairly high permeability is encountered. Building a quick filter cake on the core as well as the hole wall is imperative, to prevent invasion of the core and fluid loss to the formation. We have previously suggested a lightweight, 75-s viscosity drilling mud for coring under these lithologic conditions. A greater pump pressure is required to move this higher viscosity drilling mud through the bit opening and up the annulus formed between the drill pipe and the borehole. Where 35–50-lb/in.^{2} pressure was used for the 50-s viscosity drilling mud, 50–75-lb/in.^{2} pressure is used as coring progresses and cuttings are generated. Fluid pressure may climb as high as 100 lb/in^2. Rotational speed and penetration rate of the coring bit vary somewhat depending upon the density of the sand encountered, but they should not exceed a rotational speed of 250 r/min and penetration rate of 1 ft/5 min. If any vibration or chattering of the coring bit occurs, the rotational speed should be decreased until the operation of the drill smooths out. If the sand gets coarser or turns to a sand-gravel mixture, mud viscosity may have to be increased to as much as 100-s. Although this viscosity will probably not prevent deep mud invasion of the core, the added gel strength is needed to surround and hold the gravels in place. Whenever the viscosity of the drilling mud is increased, the pump pressure also has to be increased to circulate the fluid.

A gravel with a sand-silt-clay matrix is considered by many people to be impossible to core without causing considerable disturbance. This type of material is commonly found in glacial till and sometimes occurs in alluvium. It is usually considerably less permeable than sands, so a less-viscous drilling mud can be used (possibly in the 40-s to 50-s range) to core it. This thinner mud will results in less fluid pressure required to circulate the cuttings to the surface; even at a depth of 300 ft, the pump pressure probably is less than that needed at a depth of 100 ft using a 75-s mud. The technique used to core this type of formation is cutting rather than pushing core in unconsolidated sediments. The hardest material in the formation, the gravel, must be cut. If penetration is too rapid, the gravels will be pushed or torn loose from the matrix, completely disturbing and contaminating the core. At the assumed depth of 300 ft, probably enough weight is on the coring bit from the weight of the drill pipe; in fact, if this weight is enough to dislodge the gravel, the holdback should be adjusted to hold up some of the weight of the drill pipe. Rotational speed of the drill should not exceed 200 r/min; if chatter or tearing out the gravels is indicated, the drill should be slowed until the drill pipe is running smoothly. Using the low down pressure on the core bit and relatively low rotational speeds for coring this type of material results in a slow penetration rate (in the range of 1 ft every 15–20 min), because, even though the drill is coring in an unconsolidated formation, it is also coring rock (the gravel particles).

Photographs of cores of the type material just described are shown in figures 14–16; these photographs show that the gravels can be cored by the hydraulic-rotary coring method without tearing up the matrix. As previously mentioned, to obtain good cores of these type materials, the gravels must be cut and not merely pushed up into the core barrel. For example, drive-core samples of this formation were attempted using a 3-in.-diameter drive-core sampling barrel requiring 25 to 30 hammer blows per foot. The cores obtained using the drive-coring method were badly disturbed and consequently of such poor quality that they could not be used for analytical purposes.

The last type of lithology to be discussed under hydraulic-rotary drilling methods of unconsolidated sediments is clay. Clay is the easiest of the unconsolidated sediments to core; it is not readily invaded by drilling fluids, but it poses a problem of drillability using diamond bits. This drillability problem results from lubrication of the mud and the clay particles, causing the diamond coring bit to slide on the surface of the clay instead of cutting it. Techniques for coring clay follow. Because of the ease of forming a filter cake on low-permeability material such as clays, a lower viscosity drilling mud can be used (35-s to 40-s); with clay, use of the thinnest drilling mud possible to clean and lubricate the bit allows faster penetration rates. The coring bit may be rotated as high as 400–500 r/min when coring thick clay beds if the drill pipe rotates smoothly. This higher rotational speed, used in conjunction with a compatible downfeed pressure on the coring bit, also aids in faster coring penetration rates when coring clay. Although use of a thinner drilling mud and a higher rotational speed of the coring bit accomplishes fairly fast penetration rate, one phenomenon occurs in coring clay to impose a restriction on the penetration rate: when the diamond coring bit cuts through a clay, particularly if the clay is somewhat dense, a very close tolerance hole is cut because little or no material erodes. This results in the need for high pump pressures to push the cuttings through this tight restriction; and, even though a thin drilling mud is used, a fluid pressure as high as 100 lb/in.^{2} might be needed to accomplish this. Although forming a filter cake on clays is easy, and clays do not invade easily, a too-high fluid pressure eventually results in drilling mud invasion of the core; therefore, the penetration rate must be governed by the fluid-pressure buildup. If considerable thickness of clay is cored, drilling-mud viscosity increases, and the drilling mud may have to be thinned.

Carbide-type bits are advertised as useful for coring soft formations. We have experimented with carbide-type bits in all types of unconsolidated formations, and have found them to be unsuitable for coring unconsolidated granular materials other than clay. The carbide-type soft-formation bit with its large carbide inserts rips the grains out, it doesn't cut them. The carbide-type soft-formation bit is useful in coring clays and cutting some soft rock cores such as some sandstones and shales By using the discussed techniques and carefully using the diamond bit, the granular materials can be cut. Diamond bits are expensive, and cutting unconsolidated sediment cores with them is harder on these bits than cutting rock; however, they are the only bits that can be used for this purpose.

One problem occurs in hydraulic-rotary coring of unconsolidated sediments where high-viscosity drilling muds must be used, and the various techniques needed for this type of coring also must be used: no diamond bits are manufactured that specifically meet requirements for this type of coring. The bottom-discharge bit ports are too small to discharge viscous drilling muds that must be used without a resultant undesirable high pump pressure; because as much fluid as possible must be kept away from the inside cutting edge of the diamond core bit, excessive diamond wear occurs. Engineering design is the only way to overcome these problems, particularly the diamond setting and grade of the inside cutting face. Design engineers in the drilling industry are not concerned about this problem probably because few people attempt this type of coring, and the product market is limited. The authors have made adaptations to existing coring bits, such as enlarging discharge port sizes, recessing discharge outlets, and so forth. The diamond setting, however, cannot be changed.

Drilling Fluids

The utilization of a strictly controlled drilling-fluid program whenever hydraulic-rotary coring of unconsolidated material is done is very important. When coring unconsolidated formations, water or other thin drilling- fluid mixtures cannot be used. When coring unconsolidated materials, form a quick, thin filter cake on the hole wall, as well as on the exterior of the core, so that little or no filtrate invasion or erosion of the core occurs. Viscosity of the drilling fluid must be high, and weight must be low (fig. 17). Although some variation of the drilling fluid for unconsolidated formations is permissible, it is only in the high-viscosity ranges. When coring medium sand, we use drilling fluid in the range of 50-s to

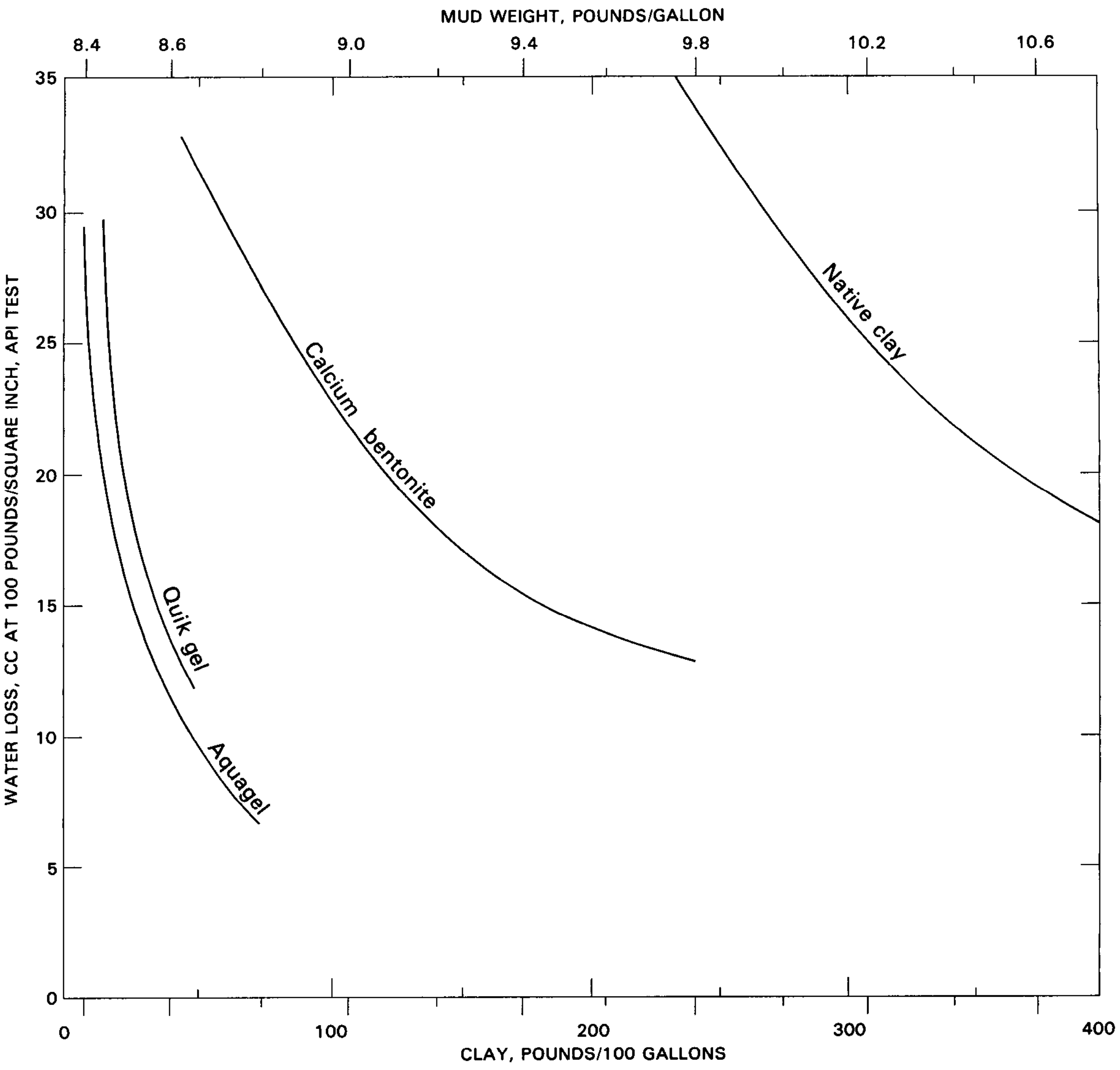


Figure 17.—Mud weight versus water loss.

greater than 100-s funnel viscosity, with 75-s being an average. In these viscosity ranges, the drilling fluid does not readily circulate through the bit openings and annulus between the drill pipe and the hole wall; it oozes through. Even with these high viscosities, the weight of the drilling fluid including cuttings weight should not exceed 9 lb/gal in order to prevent invasion of the core. In coring a medium sand, using a 75-s viscosity drilling fluid, the mud weight should not exceed 8.8 lb/gal. These high-viscosity and lightweight drilling fluid restrictions are necessary to obtain uncontaminated core from unconsolidated formations. Drilling muds having these restrictive properties are made using very high-yield (low solids) bentonites, such as Quick Gel. Low-solid polymers can be added to the bentonite mixture to hold the weight down, while still increasing viscosity. We have used Revert (fig. 18) for coring unconsolidated materials; its low solids, light weight, high viscosity, and very good lubricating qualities make it a useful drilling fluid. However, the chemical properties of Revert could possibly result in nonpathogenic bacterial contamination of the cores.

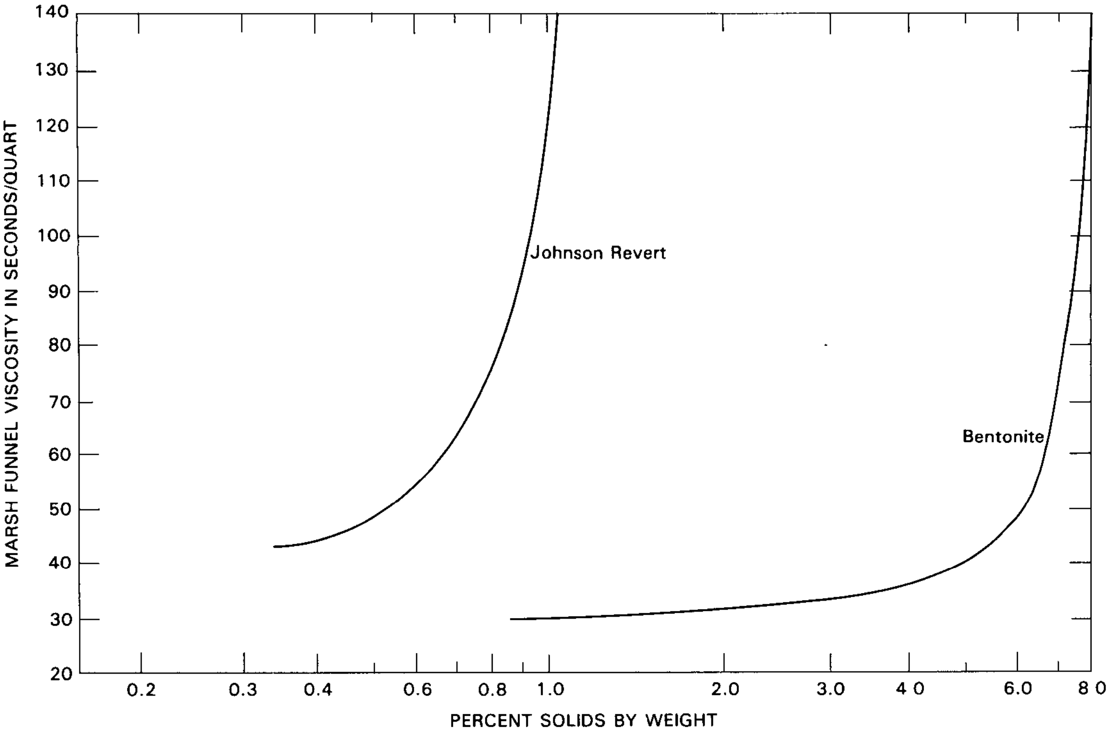


Figure 18.—Comparison between Marsh-funnel viscosity and percent solids, by weight for Revert and bentonite (Universal, 1966, reprinted by permission from Johnson Division, Universal Oil Prodicts, Inc.).

Coring Procedures in Rock

Drilling and Casing Through Overburden

In most hydraulic-rotary coring programs for rock coring, the overburden must be cased out or supported so coring can be accomplished without danger of the unconsolidated material caving or falling into the hole (fig. 10 for a schematic view). Casing out or supporting the overburden is usually accomplished in one of the following ways:

1. A heavy-wall drive casing with drive shoe attached is driven to refusal by means of a heavy drive hammer. If refusal is reached prior to encountering bedrock because of boulders, gravel, stiff clay, and so forth, a drill rod with a chopping bit or cutting bit attached is used to chop or drill the material out of the inside of the drive casing, and the cuttings are carried out of the drive pipe with the circulated drilling fluid. This chopping or drilling out may proceed some distance ahead of the drive casing, depending on the types of material drilled. The drill rod is removed from inside the drive casing, and driving of the casing proceeds as above by the addition of necessary sections of drive casing; alternate washing out and driving continue until the drive shoe is seated in bedrock.

2. Some drillers use the drilling-in method of installing casing, particularly if the overburden is fine-grained material. A diamond cutting bit on the bottom section of drill casing, and circulating drilling fluid is used to drill the casing through the overburden and down to consolidated material. If this method is used, a chopping bit may be needed to clean out accumulated debris from inside the drill casing. This drilling-in of the casing is preferred when alternate hard and soft formations are anticipated. An example of this type of coring environment would occur in basalts, where cinder zones or interbedded sediments could be encountered and result in lost circulation or caving, or in limestone, where cavernous conditions or running sands may be encountered. If the drilled-in casing method is used in these situations, the diamond cutting bit on the casing could be used to ream and advance the casing through that section of the rock cored and coring could proceed without the problems of drilling-fluid circulation loss or caving occurring.

3. A popular method for installation of casing through overburden is to mud-rotary drill through the overburden using a drag bit or roller-cone bit, and a viscous drilling mud to build a filter cake and support the wall of the hole so casing may be installed after the drill pipe is removed. The driller may install any type of casing in this method of casing installation.

4. This method for supporting the overburden is the same as that described in method 3, except no casing is installed in the hole. The filter cake and hydrostatic head of the drilling fluid in the hole is relied on to hold the overburden in place. This is the least- preferred method for supporting the overburden because of concern about hole caving and the possibility of pebbles or gravel falling to the bottom of the hole. These pebbles or gravels can result in considerable damage to the diamonds in the coring bit.

Drilling Fluids

The drilling fluid used for hydraulic-rotary coring in rock is the most variable component of the system, ranging from water to a prepared viscous, high-gel strength drilling mud. Early literature refers only to the use of water as a drilling fluid; however, modern core-drilling operations include a mud program. The reasons for drilling-fluid variation are:

1. If casing has been installed through the overburden and the rock to be cored is very dense with low permeability, water loss would not be a problem; so, considering the economics of the situation, the driller may choose not to use a drilling mud. However, a larger- capacity fluid pump would be required to remove cuttings from the hole when a low-viscosity drilling fluid, such as water is used.

2. If the cored rock is soft, the high-velocity emission of the drilling fluid at the bit will erode the core resulting in poor core recovery. If this occurs, some drilling mud must be added to the drilling fluid to remove the cuttings from the hole after the fluid velocity is lessened to prevent core erosion.

3. If the rock being cored is extremely permeable, too much water is lost to the formation; and, if water supply is a problem, then enough drilling mud is mixed with the fluid to build a sufficient filter cake on the hole wall to stop or slow down fluid loss. This may result in the mixing of a drilling mud very similar to that used for standard mud-rotary drilling for water wells: 40–50-s funnel velocity, and 8.5–9 lb/gal in weight. If the hole is being cored into formations containing hydrostatic heads greater than that of the fluid column in the hole, then drilling-mud weight will have to be increased to overcome this hydrostatic-head difference. If added drilling-mud weight is required, it should be accomplished by adding barite and not by simply letting the sand content build to a high level. A high sand content is not only abrasive to the many drill components, but it also causes considerable eroding of the core.

4. If coring is to progress satisfactorily in so-called heaving or sluffing shales, a designed drilling-mud program is necessary. Fluid enters the shale, causing hydrous swelling or disintegration of the shale, and results in sloughing or heaving. This problem can be prevented by using a low-weight, highly colloidal and viscous drilling mud or polymer that will build a quick, thin, filter cake on the shale, and thereby prevent fluid invasion, which will inhibit swelling and hydrous disintegration.

5. Design of a drilling-mud program for hydraulic-rotary coring of rock is for the benefit of the hydrologist (or other scientist) requiring core. If the cores are to be used for determinations of any chemical or other waste materials that may be contained in the pore spaces of the rock, water or thin drilling fluid cannot be used because of the danger of flushing out the constituents of interest. This problem is more pronounced as permeability of the rock increases; a designed drilling-mud program may need to be written into the drilling-contract specifications to build a filter cake on the exterior of the core as well as on the interior of the borehole. A photograph of a rotary core of an unconsolidated medium sand obtained by the hydraulic-rotary coring method is shown in figure 19; the filter cake on the exterior of the core prevented or lessened mud invasion of the core. The amount of fluid to circulate for hydraulic-rotary coring is a variable that can only be discussed in general terms. Too little fluid will not permit proper cooling of the bit and lubrication of the tool string; it does not carry cuttings away from the face of the bit fast enough, resulting in bit blockage and high pump pressures. Too much fluid can result in abrasive damage to drilling tools and components, particularly erosion of the waterways and matrix of the bit, and will result in erosional damage to the core. The correct amount of fluid is enough to

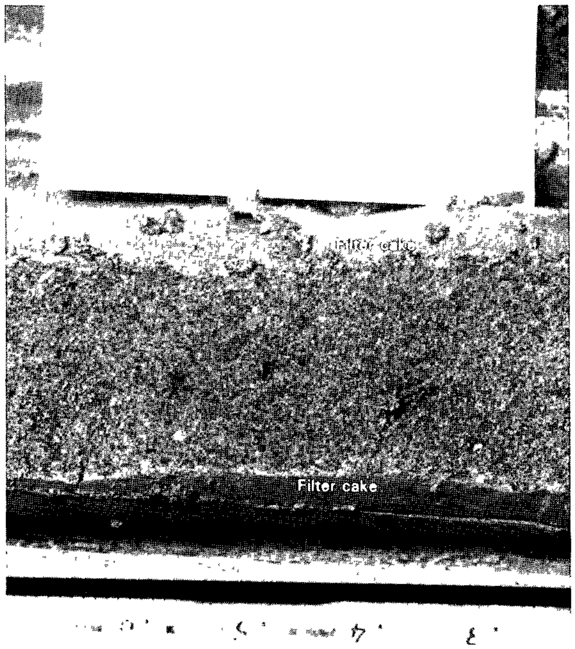


Figure 19.—Rotary core of an unconsolidated medium sand showing filter cake.

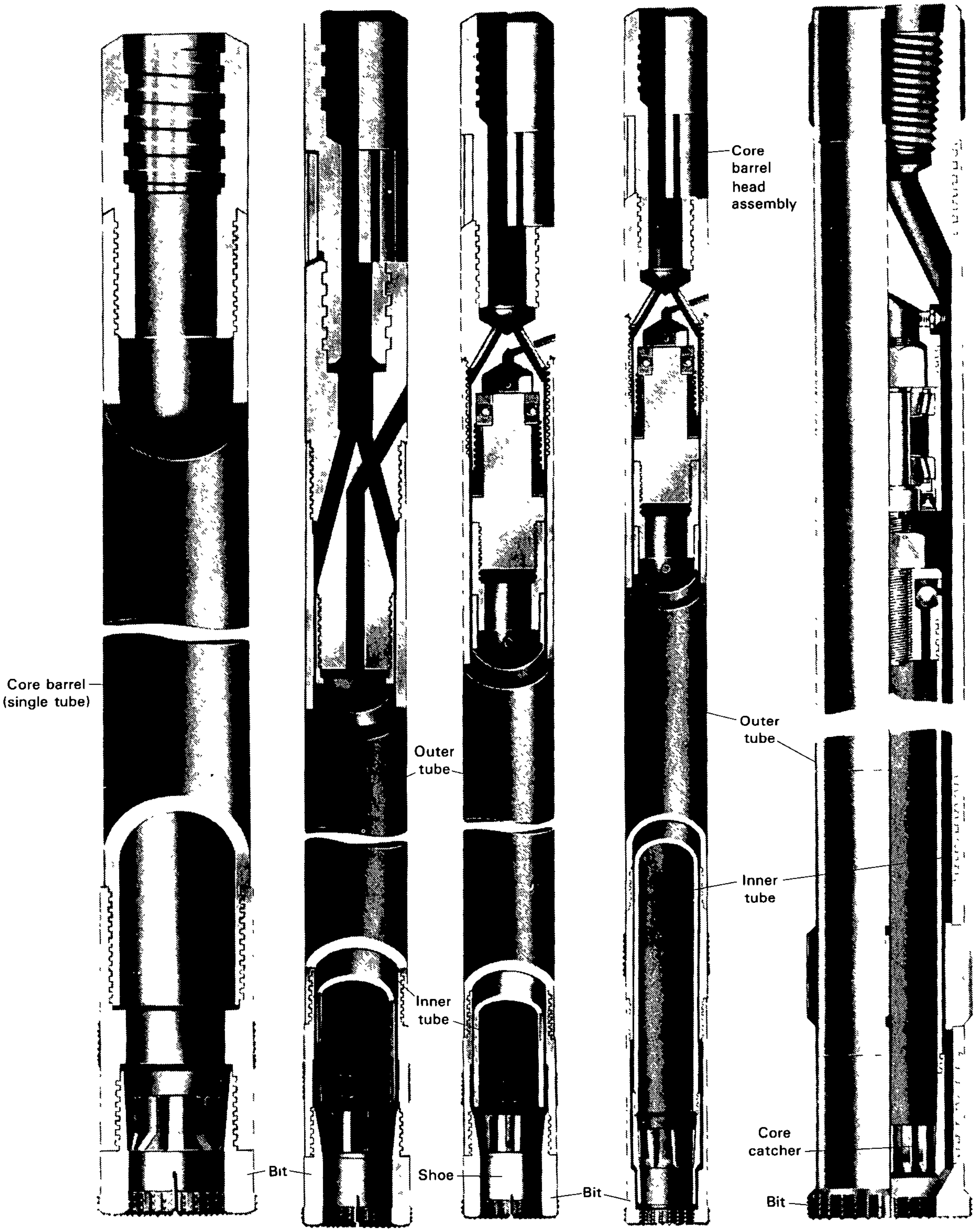
perform the needed functions but not so much that it will cause abrasive damage to both the component parts and the core. The driller will learn through experience the proper amount of fluid to use.

Coring Rock

After the overburden has been stabilized using casing or drilling fluid, a diamond core barrel (fig. 20) consisting of a double-tube barrel, a diamond-set reaming shell, a nonrotating inner barrel equipped with a core catcher and shoe, and a diamond cutting bit that meets the requirements for cutting the material, is attached to the drill pipe and lowered to a point just off the bottom of the hole. The kelly or spindle rod is connected to the top of the drill pipe by means of a mechanical or hydraulically tightened fastening chuck. Fluid is pumped through the drill pipe to establish circulation. Starting or seating in of the core barrel is accomplished using minimal down pressure and turning slowly. After the core barrel has been started, the down pressure and rotational speed are increased for obtaining optimum penetration rate in the formation being drilled. Down pressure and the rotational speed are variable, depending on the hardness of the rock and the diameter of the core barrel. Although down pressure and rotational speed are primarily dictated by the experience of the driller, the following observations can be made:

1. The down pressure and rotational speed working together control penetration rate and bit life. In the case of hard-rock coring, fairly high down pressure can be applied, if the rotational speed is compatible. When coring hard rock using an NW-size core barrel, the core barrel can safely be rotated at 600 r/min using a down pressure of as much as 2,000 lb, assuming the drill pipe is straight and no undue vibrations or chattering of the drill pipe result. If, because of vibration, the rotational speed must be decreased, the weight on the bit must also be decreased accordingly or polishing and dulling of the diamonds will occur. The rotational speed must vary accordingly with the diameter of the core barrel used since this is controlling peripheral speeds of the diamonds. For instance, an NW core barrel rotating at 600 r/min has a peripheral speed of about 460 ft/min, but if coring with an AW core barrel, it would have to be rotated at about 1,000 r/min to reach a peripheral speed of 460 ft/min. In practice, under ideal conditions using straight drill pipe in a straight hole, maintaining proper drilling-fluid conditions, rotational speeds as much as 2,500 r/min for AW core barrels, and 1,500 r/min for NW core barrels, can be achieved in coring hard, competent rock. These speeds can be determined by the competent driller, who recognizes that any vibration of the drill pipe will cause vibration and chattering of the bit, resulting in bit blockage, broken core, and poor core recovery.

2. If coring is performed in abrasive, fractured, or friable rock, the rotational speed and down pressure must be decreased accordingly to maintain smooth running of the drill pipe. If the coring bit penetrates these materials too fast, it overdrills, which breaks out pieces of rock and results in bit blockage and poor core recovery. Considering the many variable combinations of rotational speeds and down pressures that are applicable to the coring bit, correct techniques must be practiced by the core driller, because successful coring projects depend a lot upon the applied experience and intuition of the core driller. After the increment of core has been cut that corresponds to the core barrel length, the core must be broken off at the bottom of the core bit. This is accomplished by steadily retracting the drill pipe and core barrel about 1 ft (we prefer to retract the drill pipe without any rotation). The core



G Design single tube core barrel

G Design double tube (rigid type)

G Design double tube (swivel type)

M Design core barrel

Air-mud core barrel

Figure 20.—Typical diamond core barrels (Acker, 1974, reprinted by permission from Acker Drill Co., Inc.).

retainer will slide down slightly in the beveled shoe, imparting an ever-increasing grip on the core, and the core will almost always break off in the hole at or very near the bottom of the core bit. Often, the snap can be felt through the drill pipe as the core breaks. If the core does not break off after retracting the drill pipe the recommended 1 ft, slowly lower the drill pipe again to within about 2 in. of the hole bottom and again retract it about 1 ft. This procedure is recommended only if the core retainer does not catch the core on the first retraction attempt. After the core has been broken loose and prior to pulling the drill pipe for removal of the core, circulate the drilling fluid for several minutes to clear the cuttings from the hole.

Removal of Core Barrel from the Hole

After the core has been collected, the core barrel is retracted a short distance (several inches) to break off the core. If standard coring rods and core barrel are used in the coring operation, the rods are tripped out of the hole and the core barrel is dismantled in much the same manner as described in a later section, "Removal of rock core from the inner tube."

The wireline system of coring provides the advantages of not having to trip the coring rods out of the hole after each core run is completed resulting in improved hole stabilization. This hole stability is an important aspect in the hydraulic-rotary coring of unconsolidated materials; therefore, the wireline system of coring is the principal system that the Water-Resources Division uses. When the wire-line coring system and overshot assembly is used (fig. 21), it is run down the inside of the coring rod on a ¼-in. cable, spooled from the wire-line winch. When the overshot assembly reaches the inner-barrel head assembly, the overshot latching assembly engages the inner-barrel spearhead, and the inner-barrel assembly is hoisted to the surface. After the inner-barrel assembly has been removed from the drill rod, another complete inner-barrel assembly is dropped down the drill rod and allowed to settle through the drilling mud or is slowly pumped down to bottom and coring can be resumed. This removal procedure is followed for each core interval.

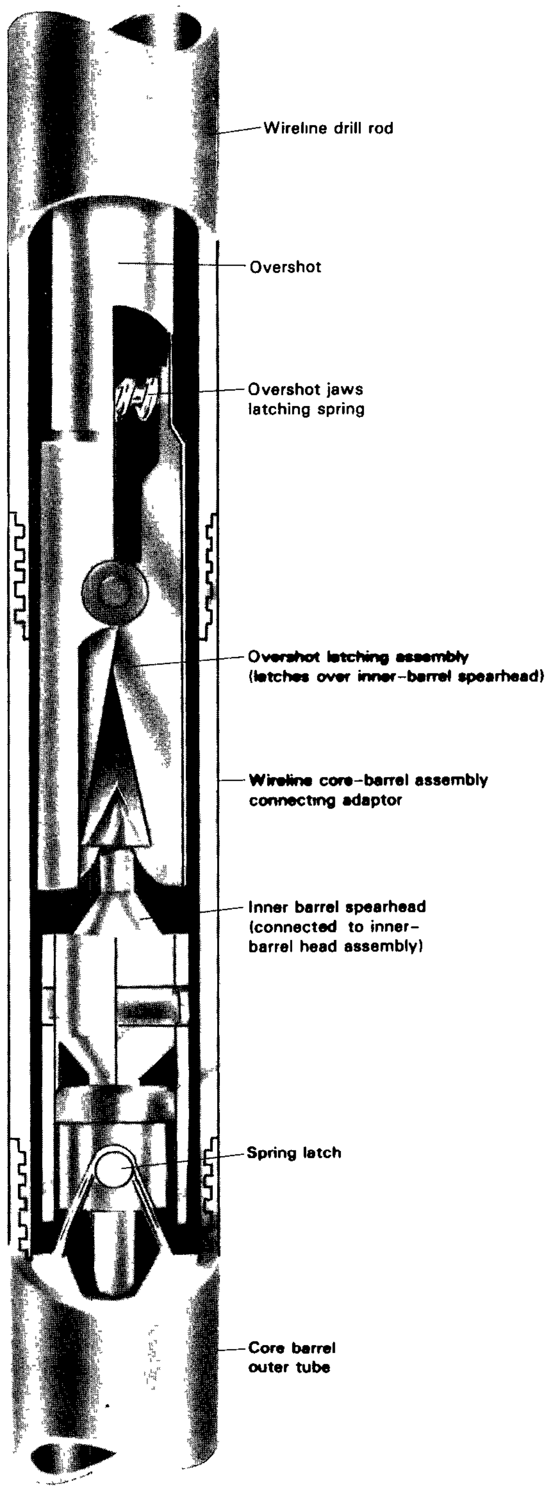


Figure 21.—Wire-line overshot assembly in locked position on inner-barrel head assembly.

Removal of Unconsolidated Sediment Core from the Inner Barrel

Removal of the core of unconsolidated sediments from a standard wire-line core barrel differs from the procedure used for removing a rock core.
The removal procedure is as follows:

1. The solid inner barrel is removed from the outer core barrel and is placed in a chain-type pipe vise. The core-retainer shoe is then unthreaded from the lower end of the inner barrel and the swivel-head assembly is unthreaded and removed from the upper end.

2. The clayey filter cake on the outside of the core will usually stick to the barrel and the core will have to be pushed out. To do this, a plunger affixed with a 5-ft extension is fitted into the upper end of the inner barrel and used to push on the top of the core. It is occasionally difficult to break the surface tension between the core and the solid inner barrel; however, when the core begins to move as pressure is exerted upon it, it usually will slide out easily.

3. When the core begins to move, a half-round trough (5-ft-long, thin-walled tubing, cut in half) is placed under the leading edge of the solid inner barrel, and the full length of the core is extruded into the trough. The trough is then placed on sawhorses or a clean platform for inspection. The cored material can now be exposed for examination and logging by trimming a thin section of filter cake off with a sharp knife.

4. After the core has been logged, a 6-ft length of thin-wall, lay-flat, clear plastic tubing is placed over the core and the trough. Plastic tubing of this type can be purchased in various diameters and different-length rolls. One end of the tubing is then tied. A felt marking pen is used to mark the core as to top, bottom, depth, hole number, and any other necessary data. After the insleeved core is marked, another half-round trough is placed over it. The core is then turned over and the trough that is still in the plastic sleeve is removed and the other end of the plastic sleeve is tied. The core trough, now holding the plastic-insleeved core, is placed against or into the end of a precut, 5-ft length of plastic pipe, and the core pushed into this pipe for further protection. Note: If the pipe used is too large to fit the core, some additional packing (plastic or paper) should be wrapped around the core to ensure a snug fit.

5. The plastic pipe is then capped and taped. The same identification that was written on the plastic core sleeve is repeated on the plastic pipe. The pipe with core enclosed should be placed in a core box for additional protection.

Removal of the core from the HQ-3 wire-line inner barrel and split-tube liner used by the Water Resources Division differs somewhat from the standard barrel described above:

1. The wire-line inner barrel is removed from the hole and placed in a strap vise, and the core-retainer shoe and swivel-head assembly are removed. An adaptor head with an internal piston that butts against a thin-wall, split tube is screwed onto the upper end of the inner barrel (fig. 22), and a quick-coupling hose that leads to a hand pump is coupled to the adaptor head. The pump is connected to, or the intake pipe is placed in, a water supply (barrel or water tank); operation of the hand pump gently extrudes the split-tube liner.

2. The split-tube liner is placed on a stand or platform, and one-half of the split-tube liner is removed. Sometimes the filter-cake stickiness causes a surface tension similar to that described for the solid inner barrel, and it is difficult to lift the split-tube liner off the core. The split-tube liner can be separated by gently tapping the upper part of the split tube while, at the same time, lifting one end to break it loose. If this does not loosen it, a putty knife is placed on both sides of the core between the split-tube liner while lifting one end of the split tube and gently prying down on the upper part of the core. This procedure may have to be done the entire length of the core because, if the top half of the the split-tube liner is stuck, the bottom half will be stuck also. A small-diameter stiff wire, a thin flexible saw blade, or an ordinary cheese-cutter blade can be bent or torqued to the exact contour of the inside of the split-tube liner and slid the entire length of the core, severing it from the bottom tube.

3. After the core is severed from the bottom section of the split-tube liner, it is placed on a clean platform and care is taken not to bend or damage the tube (while using it as a core trough). Subsequently trim a thin section of filter cake from the core with a sharp knife thereby exposing a section of clean core for examination.

4. After the core is logged, a 6-ft length of thin-wall lay-flat, clear plastic tubing is placed over the core and split-tube liner and one end of the tubing is tied. A felt marking pen can be used to

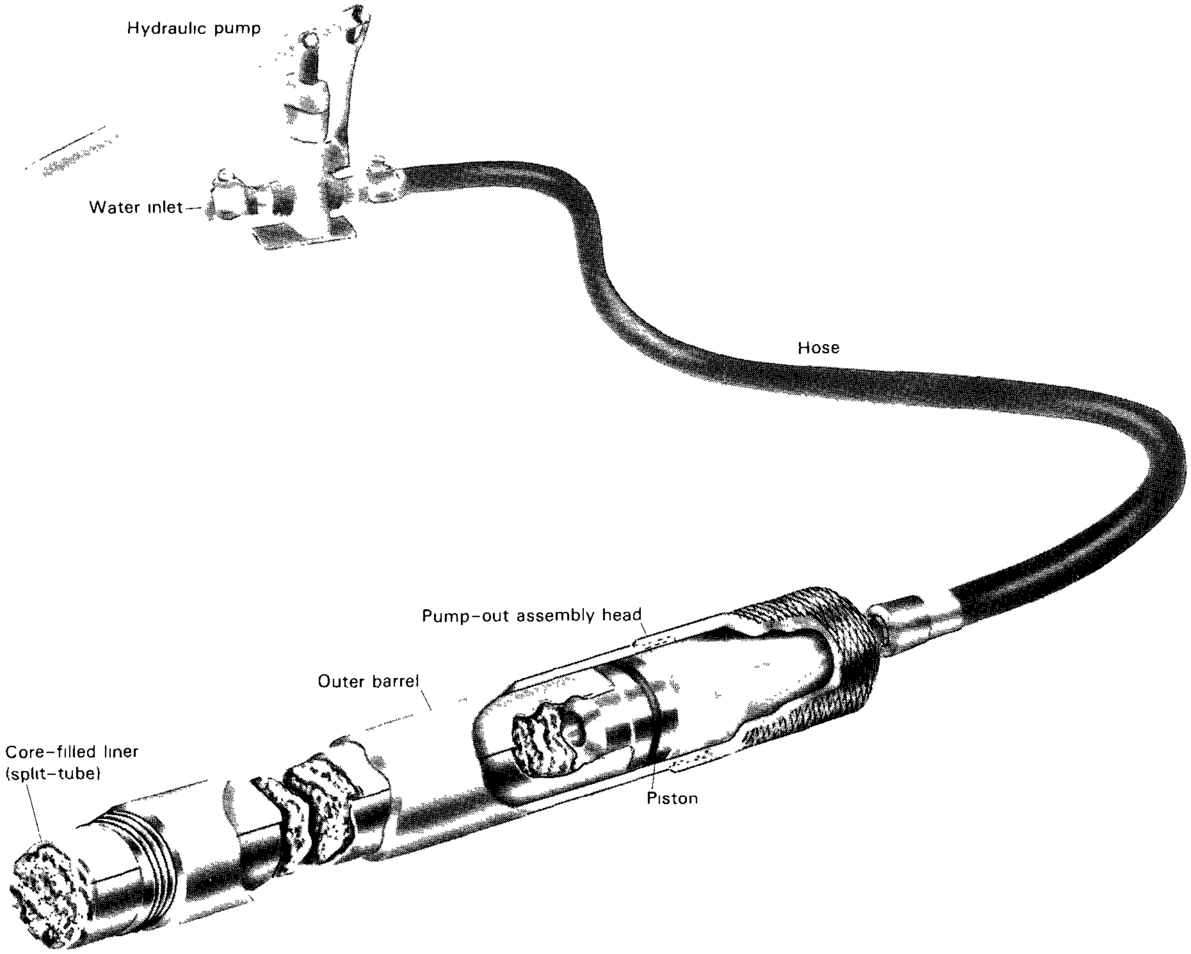


Figure 22.—Core-liner extrusion pump-out assembly (reprinted by permission from Longyear Company).

identify the core as to top, bottom, depth, hole number, and any other pertinent data. After labeling, the other half of the split-tube liner (or use a core trough) is placed over the core. The troughs can then be rolled over and the split-tube liner half that is still in the plastic sleeve removed and the other end of the plastic sleeve tied. The split-tube liner half or core trough holding the plastic-insleeved core is placed against or into the end of a precut, 5-ft length of plastic pipe, and the core is pushed into this pipe for further protection. If necessary, additional packing material should be wrapped around the core so that it fits snugly in the protective pipe.

5. The plastic pipe is then capped and taped. Repeat the written core identification on the plastic pipe and place the pipe in a core box for additional protection.

Removal of Rock Core from the Inner Tube

After the core barrel is removed from the hole and placed in a pipe vise or on a clean platform, the diamond bit is removed using a pipe wrench or chain wrench, and extreme care is taken not to affix the wrench to the bit or reaming shell opposite any diamonds. Then the outer tube is broken loose and removed from the core-barrel head assembly exposing the inner tube. The inner tube is disconnected from the inner part of the core-barrel head assembly and the core-retainer shoe removed. Then the inner tube is slightly inclined to allow the core to slide into the segmented compartments of the core boxes. The core is marked with the depth, top and bottom of the core, and any other pertinent information.

After reassembling the core barrel and before placing the bit back on the bottom of the core hole, carefully measure the core barrel and drill pipe. The reason for doing this is that a short stub of core often projects up from the bottom of the hole because the core retainer has broken the core off 1 or 2 in. above bottom or, occasionally, a segment of the core has fallen out of the inner tube when the core barrel was tripped to the surface. Attempts should not be made to core over or through these obstacles, or blockage of and damage to the core bit will result. If there is core debris remaining in the hole, a chopping or rotary bit must first be used to drill and break up the debris and drilling fluid circulated to clean the material out of the hole prior to resuming further coring in the hole.

Table 3.—Lost-circulation materials

Comparatitive products		Description
Baroid	Magcobar	
Wall-Nut	Nut-Plug	Crushed granular nuthulls in fine, medium, coarse, and flour grades.
Aspen Fiber	Magco-Fiber	Specially processed blend of aspen fibers of controlled length.
Micatex	Magco-Mica	Crushed muscovite mica flakes in fine and coarse grades.
Hyseal	---	A blend of various-size particles of ground paper products.
Fibertex	---	Processed cane fibers.
Jelflake	Cel-O-Seal	Shredded cellophane film

Lost Circulation of Drilling Fluid

Partial or complete loss of drilling-fluid circulation sometimes occurs when hydraulic-rotary coring of rock is performed. This loss results from encountering fractures or high-intergranular permeability in the rock, large solution openings in limestone-associated rocks, and cavernous or scoria-cinder zones in basalts (Teasdale, 1980). Blind coring is sometimes attempted (no drilling fluid circulated to the surface); however, this method could result in stuck or lost drill pipe.

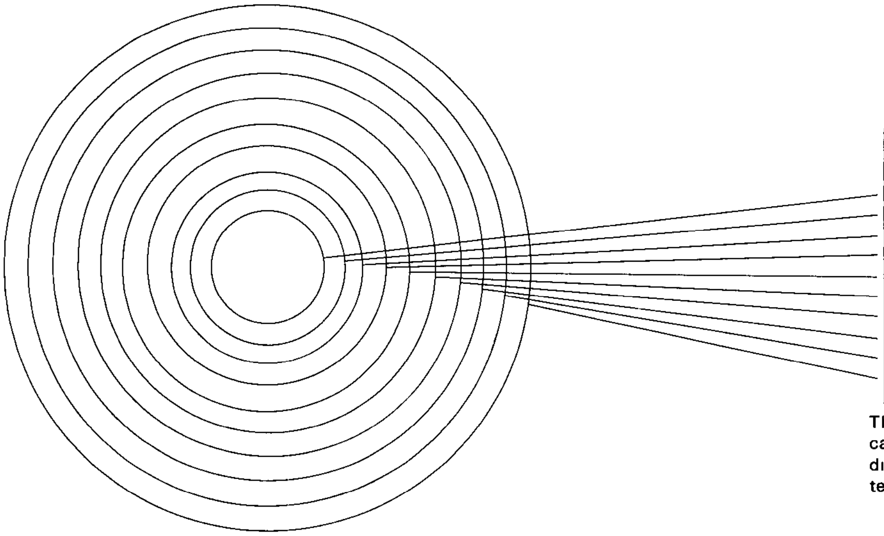
If the coring is being done using a prepared drilling mud, it is often too expensive to continue losing drilling fluid in a lost-circulation zone. Recommendations for regaining circulation of drilling fluid are as follows:

1. If the loss of drilling fluid zone results from high fracture or intergranular permeability of the rock, it may be possible to regain drilling-fluid circulation by spotting the zone with 75-s to 100-s viscosity, high-yield bentonite. If this alone does not stop the fluid loss, some lost-circulation materials listed in table 3 should be added to the drilling fluid used for spotting the zone of lost drilling-fluid circulation.

2. The methods suggested in recommendation 1. will often work whenever scoria or cinder zones are encountered in basalts (particularly if one or more of the recommended lost-circulation materials are used in the drilling fluid used for spotting the zone).

3. circulation zone is of a cavernous nature, it must either be cemented completely off or casing installed through it. If cementing of the cavernous zone is attempted, it should be done by introducing the thickest cement slurry (with a quick-set additive) that will flow down the tremie pipe. The slurry should be added through the tremie pipe in small batches to accomplish a buildup of the cement, instead of pushing it back into the cavernous zone. For a detailed review of cementing practices in core holes, see "Diamond Drill Handbook" (Cumming, 1969). Halliburton and other well-cementing service companies provide many cementing services. If the cementing job is extensive, it would be economical to have one of these service companies (with the proper equipment and expertise to perform all kinds of large cementing jobs) do the cementing.

4. Casing through cavernous, lost-circulation zones might be more economical than cementing off the problem areas and can be done in one of the following ways: (1) if the drilling-in method was used for casing through overburden, the driller may attempt to ream the hole out with the diamond-casing bit and extend the original casing through the lost-circulation zone; or (2) if extending the original casing through the cavernous zone is not possible, then the next smallest size casing would have to be installed and telescoped through the existing casing and set through the lost-circulation zone. This will require that a smaller core barrel be used when coring operations are resumed. Core-drilling



REFERENCE SYMBOLS	CASING DIAMETERS mm	inches
RX or RW	36.5	1-7/16
EX or EW	46.0	1-13/16
AX or AW	57.1	2-1/4
BX or BW	73.0	2-7/8
NX or NW	88.9	3-1/2
HX or HW	114.3	4-1/2
PX or PW	139.7	5-1/2
SX or SW	168.2	6-5/8
UX or UW	193.6	7-5/8
ZX or ZW	219.0	8-5/8

The DCDMA system of standardizing casing sizes allows a smaller size diameter casing to be used for telescoping a drill hole

Figure 23.—Illustration of Diamond Core Drill Manufacturers Association W-Series flush-joint casing classification and dimensions (reprinted by permission from Diamond Drill Contracting Co.).

written contract specifications should be written to allow for standardized nesting of flush-joint casing and drill pipe to allow telescoping of casing when core drilling; different designated casing (HW, NW, and so forth) fit one inside the other, with necessary clearances for circulation of fluid and passing through the corresponding designated core barrel (fig. 23).

Drilling-Mud Pit Construction

The necessity of using high-viscosity drilling fluids for coring unconsolidated materials presents problems in settling out cuttings, which, if not settled out, would cause excessive weight of the drilling fluid resulting in greater hydrostatic head of the drilling mud column and consequently deeper drilling-fluid invasion. The manner and size of the drilling-mud pit construction is important to the cuttings settling process because the drilling mud must keep moving, if the cuttings are to settle out of suspension. High-gel-strength drilling fluid is a semisolid when not moving and will not allow cuttings to settle out. Construct two pits, each to a depth of about 6 ft, a length of 10 ft, and a width not to exceed 2 ft (the narrow width keeps the mud moving). In addition to these settling pits, two or three shallow (about 1-ft deep) primary settling pits should be excavated in the narrow mud ditch leading from the core hole to the first settling pit. (The mud ditch should be at least 15 ft long.) During the coring operation, these primary settling pits and the ditch must be constantly cleaned out, because the higher velocity of mud flow in the ditch maintains highest fluid level of the gel, resulting in the cuttings settling out. If proper clean-out of the primary settling pits is maintained and the first settling pit is periodically stirred or agitated, half of the suspended cuttings will be removed. However, if the periodic stirring and agitation of the drilling fluid in the first settling pit does not adequately remove enough cuttings to lower the drilling-mud weight sufficiently (less than 9 lb/gal), the fluid in the pit can be continuously circulated. The intake end of the centrifugal pump hose used for circulating the cuttings-laden drilling fluid should be submerged to about one-third the depth of the settling pit so as not to disturb the cuttings already settled in the pit bottom. Also, the discharge hose should be horizontally submerged in the settling pit so as not to stir the cuttings up from the bottom of the pit. If the viscosity of the drilling mud is increased by the addition of natural clays during the drilling process, drilling-mud thinning additives or water need to be used to decrease the drilling-mud viscosity. This technique will result in better settling out of cuttings; however, the drilling-mud viscosity should not be reduced to a point where mud invasion of the core can occur. The final suggested method for maintaining proper mud control, if the previous methods are not successful, is to drain and clean the settling pits out and refill them with a new drilling-mud mixture.

Air-Rotary Coring

Air-rotary coring of rock is an established procedure that uses air instead of a water-laden drilling mud to circulate the cuttings out of the hole; many core drillers prefer this method to mud-rotary coring. In some instances, the air-rotary coring method cuts faster and provides less-contaminated core. Our discussion of the method will be very brief and describes some advantages and disadvantages so a hydrologist can decide if it is the proper method to specify, considering the intended use and analysis of the core.

Equipment and Accessories

Much of the equipment used for air-rotary coring is basically the same type of equipment as that used for hydraulic-rotary coring. Drill pipe used for coring by both methods are interchangeable and wire-line coring or conventional coring can be accomplished using either air-rotary or hydraulic-rotary drilling method. Air-rotary coring bits and core barrels are constructed with discharge ports and air passageways larger than those used for hydraulic- rotary coring; otherwise, they are quite similarly constructed. The outside diameters of the diamond or carbide cutting matrices on air-rotary bits and core-barrel reaming shells are also slightly oversized as compared to the outside diameters of hydraulic rotary or conventional-type drilling-mud circulating bits and reaming shells. Hydraulic-rotary core barrels and coring bits can be modified for use in air coring; however, modifications must be fairly extensive (Teasdale and Pemberton, 1984).

Coring Procedures in Rock

Basic techniques of air-rotary coring are almost identical to techniques of hydraulic-rotary coring: air, rather than a drilling mud, is circulated to lift and carry the drill cuttings out of the hole, and, at the same time, cool the bit. All working components are the same, except the mud pump is replaced with an air compressor. In air-rotary coring, the same hydraulic-rotary problems of loss of circulation can occur, and, if the additives described in the following section are not adequate to stop lost circulation, more positive measures of cementing and casing out those zones may be needed.

The Water Resources Division of the U.S. Geological Survey sometimes contracts for air-rotary coring in possibly contaminated or known contaminated lithologic environments. Special coring procedures are used, such as grouted in-surface casing; using drive-core or other samplers for obtaining cores of unconsolidated interbedded sediments; and using only wire-line-coring methods, to prevent smearing or downward contamination of the hole that could occur if conventional coring (tripping in and out of the hole) methods were used. For discussions of these precautionary methods, see "Hydrology of the Solid-Waste Burial Ground, as Related to the Potential Migration of Radionuclides," (Burgus and Maestas, 1975).

Drilling Fluids

The drilling fluid used for air-rotary coring is air, but it occasionally has additives, such as water, foam, polymers, and bentonite gels injected to: (1) cut down airborne dust and prevent sediment balling; (2) aid in removal of cuttings at lower air velocity, as well as removal of water in saturated zones, and (3) seal off lost circulation zones. For a more detailed description of these additives and how they are used, see "Water Well Technology" (Campbell and Lehr, 1973, p. 121–125) and commercial catalogs from most drilling-additive supply companies. The velocity and volume of air required to lift cuttings out of the hole are variables that are related to the specific gravity of the particles and to the volume of the annulus formed between the drill pipe and borehole wall. Generally, an average uphole air velocity of 3,000 ft/min is required for drilling materials to remove drilled cuttings having an average specific gravity of 2.6 from the borehole. Also required is some amount of additional air to overcome the effects of whatever volume exists in the annulus plus any unknown air loss to void spaces. Detailed explanation, tables, and formulas for calculating air velocity and volume requirements for drilling various diameter holes with arious diameter drill pipe are available in "Water Well Handbook," (Anderson, 1971, p. 85–90). Air compressors used for air-rotary coring vary (from greater than 300 lb/in.^{2} down to 40 lb/in.^{2}) in their pressure output; however, the industry tends to use higher-volume, lower-pressure compressors.

Methods for removal of the core barrel, removal of core from the inner barrel, and handling of the core are the same, with one exception to that described in the hydraulic-rotary coring section. This exception is in the handling of core that is cut in a suspected or known contaminated area. Contaminated core must be handled extremely carefully to insure personnel safety and to avoid contaminating the cut core. For an outstanding description of the proper way to handle core from this type of environment, see Burgus and Maestas (1975).

Problems Encountered

Contamination of Core

Problems of core contamination from the air-rotary coring method are rarely covered in the literature; as a consequence, those problems are ignored. Contamination resulting from filter caking or core invasion that may occur if some of the previously mentioned additives are used in the air are not as great a cause for concern because they can be seen and possibly even corrected. However, there is a need to be concerned with the contamination processes that cannot be seen or even understood.

If geoscientists wish to obtain a core sample from a formation for measuring moisture content, they would probably specify air-rotary coring rather than mud-rotary coring, because mud-rotary coring would contaminate the sample and air probably would not. They are partly right: air might not contaminate the sample with foreign materials; however, it will possibly dry or blow a percentage of the moisture out of the sample. An experiment conducted by the research-drilling project provides an example of air-drying of moisture in a core. A 20-ft interval of a soft sandstone with medium-sand grain-size, was cored, using three coring methods: (1) air rotary, (2) mud rotary, and (3) drive core. Drive-core samples were used as a control assuming no moisture change. Mud-rotary cores were analyzed, and results showed moisture increases in the range of 2 to 6 percent. Air-rotary cores were analyzed and showed moisture decreases ranging from 22 to 45 percent. Not only was the moisture dried or driven out of the air-rotary cores, but those cores also indicated temperatures in the range between 110°F and 123°F, even though they had been collected from a formation having an ambient temperature of about 60°F.

The same result has been observed elsewhere. It is easy to understand the possibility of the air, even under low pressure, driving fluid out of a fairly permeable material; however, heating of the core is contrary to the literature. Supposedly, the air that is heated as it moves through the compressor, the swivel, and down the drill pipe should cool as it expands. As it leaves the bit restrictions and moves into a greater volume area, it should cool and provide cooling to the bit. But, this principle does not occur, at least in many instances, in air-rotary coring. Possibly, the observed heating effect occurs, because, although much of the air is returned to the surface of the borehole, some of it goes into even more restricted pore openings in the formation, and the hot air emitting from the bit retains or even generates additional heat.

Whatever the reasons for these problems, they do exist, and the geoscientist should consider them when planning the intended uses and analyses of the core. If considering only the physical properties of the rock—porosity, permeability, and density—drying or driving out moisture has no particular deleterious effect. However, if looking for certain chemical constituents or radionuclides that may be contained in the pore water of a permeable rock, then the risk is that that constituent also may be driven out.

Handling of Cuttings and Dust

Air-rotary coring generates a considerable amount of dust and cuttings during the process of coring. Usually, this dust is blown through a cyclone separator, where the larger particles are separated out; the dust is directly discharged to the atmosphere, sometimes through a large hose or pipe located some distance from the drill rig but often right at the separator. This dust poses health problems that should not be tolerated. If air-rotary coring is being conducted in contaminated environments, no dust should be allowed to discharge to the atmosphere. We have referred to and praised the efforts of the 1975 Radioactive

Waste Management Complex Core Drilling Program, but the cited example of dust handling (released to the atmosphere downwind) is not a good one (Burgus and Maestas, 1975).

Any specifications written for air-rotary coring should include suggested requirements similar to the following for dust control:

1. A pit or tank should be constructed that can be filled with water at an elevation lower than the cyclone separator. A perforated pipe is placed in the water and coupled to additional pipe or hose that reaches back near the separator. The dust from the separator is then circulated through the submerged perforated pipe, so that the dust will either remain in suspension in the water or settle to the bottom of the pit or tank. Another in-line blower should be coupled to the outlet of the separator and the discharge line with suitable ducting to avoid any restrictions on the air moving from the hole and through the separator.

2. Another airborne-dust and cuttings-discharge subassembly, designed and built by drilling project personnel, is discussed in detail by Warren E. Teasdale and Robert R. Pemberton (1984). The subassembly was constructed from a section of flush-joint casing and a machine-shop-fabricated packing gland, and it used rubber rings to effect a dust seal between the drill pipe and packing gland. A discharge hose was run from the casing subassembly to a water tank for cuttings and dust collection as air coring was being carried on.

TECHNIQUES OF SAMPLING

Procedures of Sampling and Testing in Auger Drilling

Solid-Stem Augers

Samples obtained from solid-stem auger-drilled holes usually are a mixture of the penetrated materials. Material samples that are deposited around the surface perimeter of the hole are representative of the penetrated materials; however, they are a mixture of several feet of the lithology encountered by the drill head. With experience, the driller can feel some textural changes while drilling at the approximate depth at which these changes are encountered in the hole. These notations, combined with collected samples, make a fairly reliable lithologic log. Periodic reaming of the hole is necessary to ensure that auger returns are representative of the penetrated zone. Disturbed auger samples may be used for determinations of particle-size distribution, specific gravity, and lithologic or mineralogic analysis, as an inexpensive analytic procedure. Disturbed materials may be repacked for hydraulic-conductivity tests if no undisturbed samples are available, but the validity of such tests is questionable. If disturbed materials are used, the following need to be considered when applying the hydraulic-conductivity test results to the field situation: (1) material returned to the surface by auger drilling rarely represents actual particle-size distribution in penetrated sediments, especially when auger drilling in saturated materials; (2) loose, granular materials encountered in the hole probably will be more prevalent than fine-grained materials in the sample appearing at the surface, because fine-grained materials may be left behind; and (3) further segregation of particle sizes occurs rapidly as granular materials are vibrated; in most cases, coarser materials are continuously returned ahead of finer materials. Thus, generally, a sample returned to the surface will not represent true lithologic conditions through the entire depth of the hole, nor can it be considered entirely representative of conditions at any given depth.

In addition to collecting disturbed-cuttings samples delivered at the surface when drilling with solid-stem augers, drive-core and even undisturbed Shelby-tube samples (see p. 72) can be collected at the bottom of the hole. However, sloughed or caved materials first need to be removed from the bottom of the hole.

Solid-Stem Auger Sampling in Unsaturated Materials

If a formation of interest is encountered in the process of auger drilling, the following techniques for securing a core sample may be used.

1. Remove the auger so all the cuttings on the auger flight do not fall back to the bottom of the hole. This usually is best accomplished by a very slow clockwise auger rotation, while pressing into the

material as hard as possible. This will result in the cuttings packing on the bottom of the auger flights and not falling back to the bottom of the hole, if the augers can be removed from the hole with no rotation (deadsticking). After the augers have been removed from the hole, run a steel tape equipped with an adequate sounding weight down the hole and determine the exact thickness of fill. Most auger-drilled holes will remain open above the saturated zone, and the amount of fill usually will be only the material that sifted down past the auger flights, probably not more than a few feet.

2. Prior to any coring in the hole, cuttings in the bottom may be removed by one of the following methods:

a. Assume the depth of the hole has been measured, and 4 ft of loose cuttings are at the bottom. To remove these cuttings, fasten a 5-ft length, 4-in.-diameter spoon sampler (fig. 24) to a section of the drill rod commonly used for drive coring. Lower the spoon sampler to the top of the cuttings by adding the necessary number of drill rods. The drill rod is then chucked into the kelly drive, and the spoon sampler is rotated and pressed into the material to be removed; as drilling out progresses, the cuttings will be fed into the spoon-sampler barrel. Several trips back into the hole may be required to accomplish the clean out. When the depth of the original bottom of the hole is reached, exert an additional downward thrust of approximately 1,000 lb to the drill rod, and, at the same time, slow the rotation and push the sampler an additional 6 in. into the undrilled material. This technique will tend to block the bit and assure that the cuttings stay in the barrel as it is withdrawn from the hole. After this clean-out procedure is complete, the hole is again accurately measured to confirm that all debris has been removed.

b. Cuttings can also be removed from the bottom of the hole by running in a solid- or split-barrel sampler equipped with a basket-type lifter. Drive the sampler into the cuttings by using a drive hammer until the barrel is full, then bring it to the surface for unloading; more than one trip into the hole may be necessary, depending on the quantity of loose cuttings in the bottom of the hole. The use of a larger clean-out barrel other than the one used to collect a sample allows adequate clearance for the sample barrel so that the sample is not contaminated. For example, a 4-in. split-barrel would be appropriate for clean-out when a 3-in. split-barrel will be used to collect a sample.

3. After confirming that the hole has been cleared to the point of desired sampling, several sampler types can be used to obtain representative samples or cores from the hole, depending on the types of materials to be penetrated and the intended use of the samples. One sampler that may be used is the spoon sampler (previously described as a clean-out tool). Lower the spoon sampler to the bottom of the hole on a string of N-size drill rods; the drill rod, fastened to the drill-rig drive mechanism, and the spoon are slowly rotated and pushed into the material being sampled. Although the spoon sampler is 5-ft long, the operator should not try to obtain a full 5-ft penetration with the sampler, because as the sampler cuts the unconsolidated but dense materials, they will be disturbed, particularly if they are noncohesive, and volume will increase resulting in more sample footage in the barrel than has actually been cut. Therefore, cut only about 4 ft to avoid overfilling the barrel and to decrease difficulty in later removal of the sample from the barrel. After the sample has been cut, the barrel is returned to the surface; the cutting shoe is removed; and the sample is removed by tapping the outside of the barrel. Note that these samples collected with the spoon sampler are disturbed and are, therefore, suitable only for visual inspection on site or for general classification and testing in the laboratory (grain-size determination, specific gravity, and so forth).

4. Another sampler that may be used in a clean solid-stem auger-drilled hole is a split-barrel drive sampler with liner(s) (fig. 25). Drive sampling usually provides a representative sample, although not an undisturbed sample, except under certain formation conditions. This sample always is adequate for most conventional laboratory analyses, including various chemical analyses and determination of waste products in the sampled environment; it also is valuable for determining moisture contents. Cutting or collecting a drive sample is a relatively simple operation. The 3-in.-diameter drive-core barrel is lowered to the bottom of the hole on drive or drill rods. A reference mark is made on the rod denoting ground surface or some arbitrary point on the drill rig, and a 20-in.

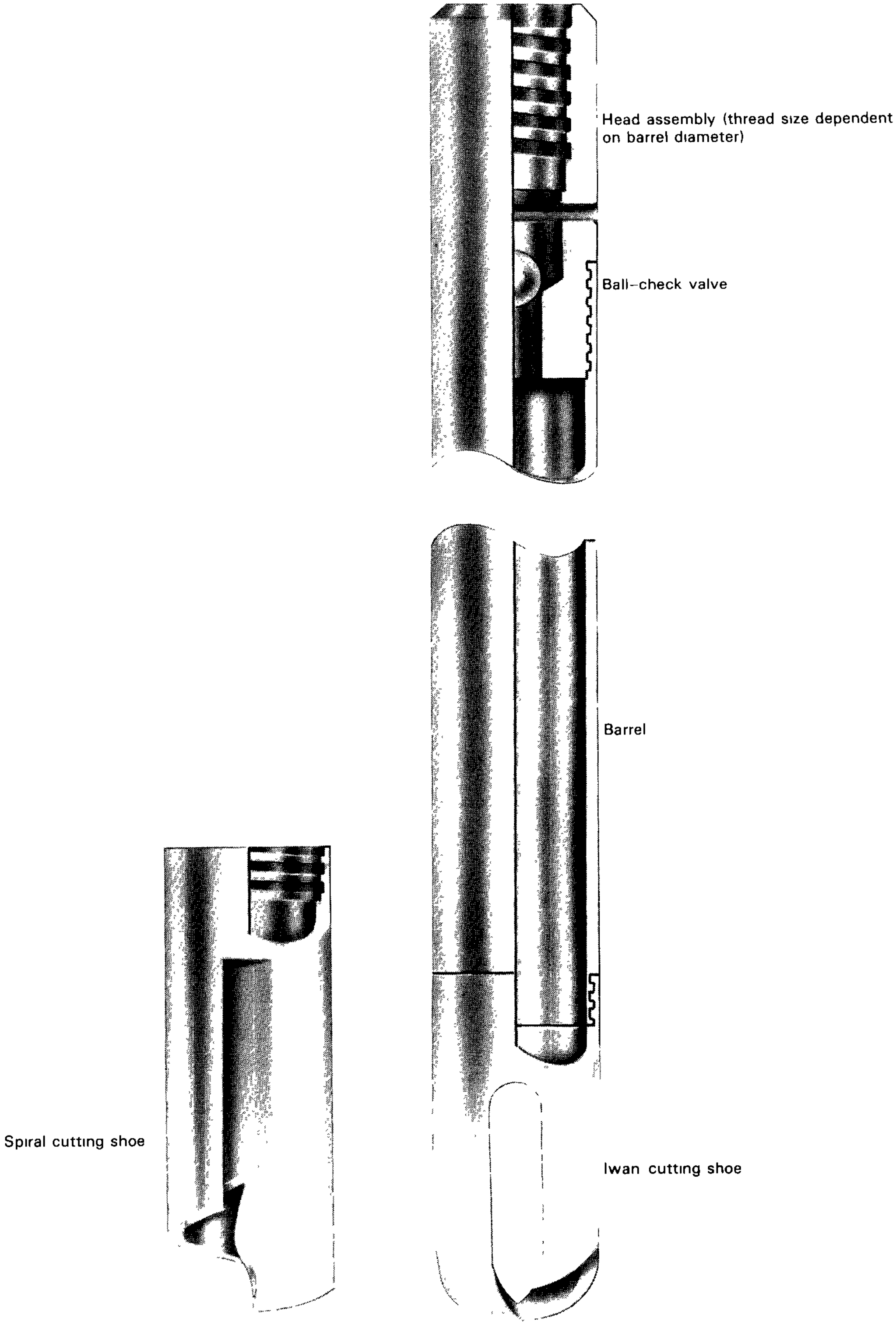


Figure 24.—Spoon sampler and cutting-shoe types.

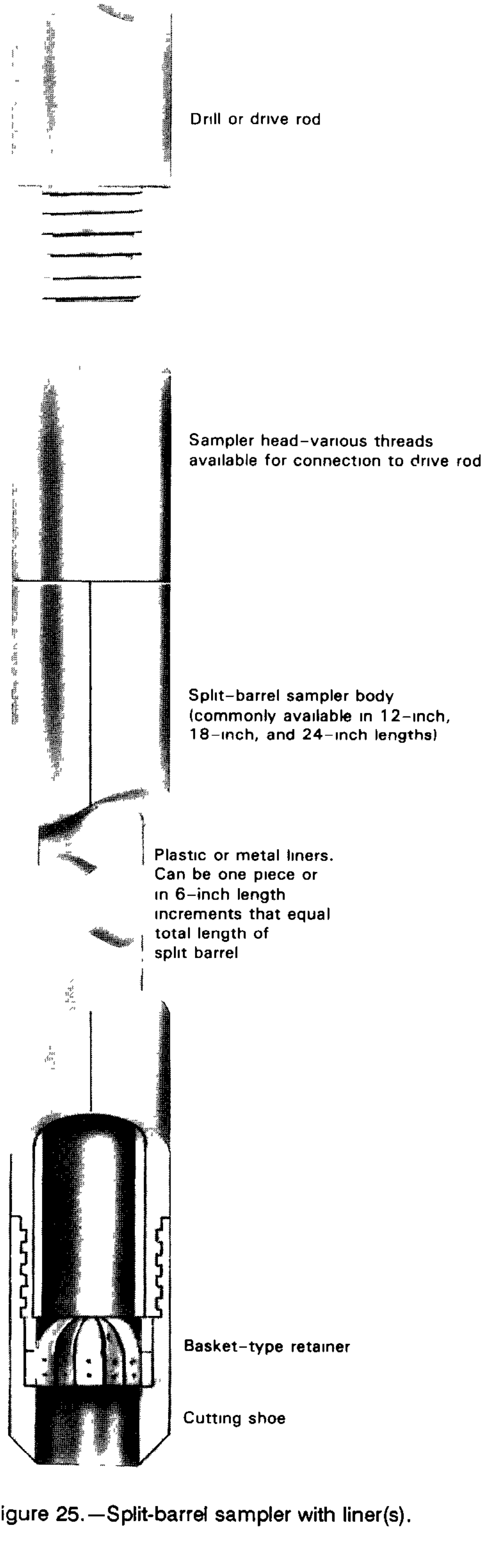


Figure 25.—Split-barrel sampler with liner(s).

measurement is made above that initial reference mark for determining the depth of the drive. Although 18 in. is the length of the barrel (containing three 6-in. liners), an additional 2-in. drive is needed to allow for the length of the cutting shoe below the barrel and inner liners. First, attach the rods to the hydraulics of the rig and push the barrel into the formation being sampled. Note: As much as 5,000 to 6,000 lb of downward thrust can be exerted on good-condition drill rods without any damage to rod or barrel. This can be accomplished if the formation is not too dense or gravelly; it will result in a much less disturbed sample. If the denseness or texture of the material being sampled prevents pushing the sampler through the material, then the driving mode is used. Attach a 140-lb or 300-lb slip-type drive hammer to the top of the drive rod, lapping a 1-in. Manila rope around the cathead of the drill rig (two laps for 140-lb hammer and three laps for 300-lb hammer), and alternately raise and drop the weight of the hammer on the drive rod. Try to keep the free-fall distance of the hammer to 30 in. at all times to allow a physical means of comparison between samples by comparing the number of blows required for penetration of each sample. The number of hammer blows required to drive a 3-in. sampler to the prescribed 20 in. varies from a few to as many as 100 or more blows depending on the density and texture of the sampled material. More hammer blows will result in greater sample disturbance and, at some point, will cause damage to the barrel and cutting shoe. A decision, therefore, needs to be made as to the importance of obtaining that particular sample. A rule-of-thumb for refusal of drive sampling with a 3-in. barrel, using N-size drill rods and a 300-lb hammer, is 100 blows per foot. This practice does not meet the American Society for Testing and Materials (ASTM) drive-sampling standards (discussed in a later section). Occasionally, samplers encounter large gravel or a boulder that will not go into the sampler, which causes refusal. Hitting a boulder or hard rock is recognized by the drive rod bouncing up each time the hammer strikes it. If this occurs, immediately stopping any driving attempts will avoid considerable damage to the cutting shoe and barrel. After the sampler has been pushed or driven to full or refusal depth, it may be freed from the bottom of the hole in one of the following ways:

a. The preferred method is to attach the drive rod to the hydraulic drive of the drill rig and pull up slowly until the sample barrel is free from the penetrated section. The rod is then disconnected from the rig hydraulics; a swivel is attached to the rod; and the rod and sampler are removed from the hole by the rig winch.

b. Rarely does the sampler become so imbedded that the rig hydraulics or winch will not break it loose. However, if it does not pull readily, reattach the drive hammer and use the cathead to impart an upward blow to dislodge the sampler. After it has been dislodged, use the above method (a) to return the sampler to the surface. The split-barrel sampler is then disassembled by removing the head assembly (containing the ball-check valve) and the cutting shoe. Separate the two-piece barrel wall and remove the sampler core liners containing the practically undisturbed sample. The liners may then be capped or otherwise sealed.

c. An additional sampler that may be used in clean, solid-stem auger-drilled holes is a thin-walled Shelby-tube sampler (fig. 26). This sampler provides a nearly undisturbed sample, but only in mostly cohesive materials and soft formations. The sampler has no capability for sampling gravelly material. Shelby tubes come in a variety of diameters and lengths; a 3-in.-diameter, 36-in.-length tube is considered standard for this discussion. The Shelby-tube sampler with head assembly is attached to the N rods and run to the bottom of the hole by adding necessary increments of additional rod. When the Shelby-tube sampler is set on bottom, the top section of rod is attached to the hydraulic drive of the drill rig, and the sampler is thrust into the material at a steady and fairly fast rate. If the material being sampled is soft, a full-length penetration of the sampler will be accomplished. However, if the material is granular or dense, only partial penetration may be accomplished using the hyraulic-push method. Whatever the penetrated depth, the sampler needs to be removed after reaching thrust refusal if the sample is to remain undisturbed.

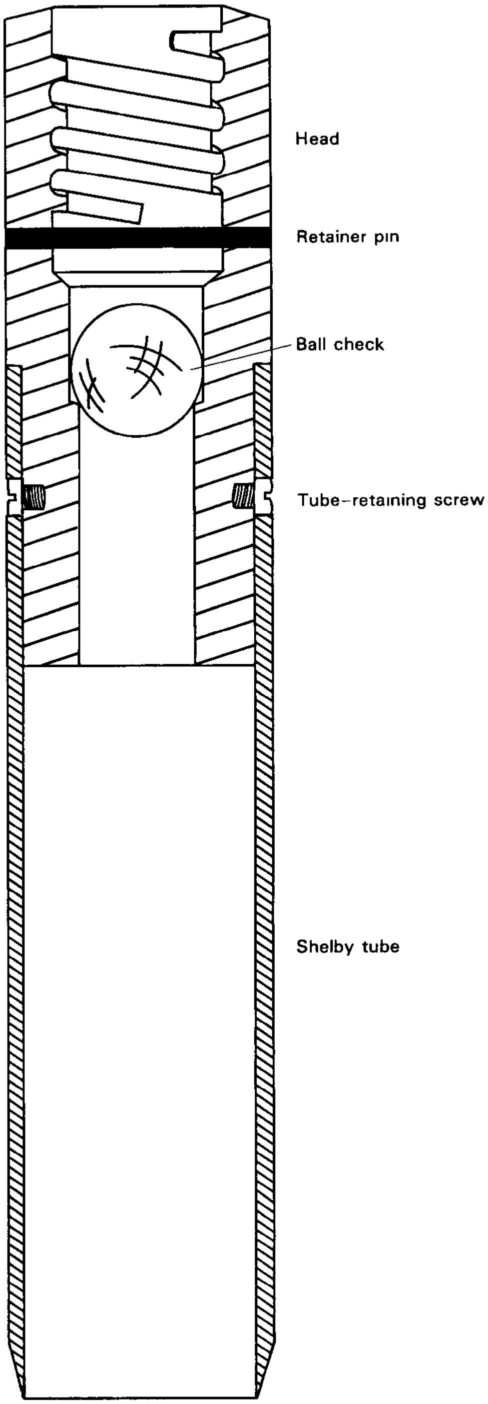


Figure 26.—Shelby-tube sampler.

The Shelby-tube sampler may be removed from the sampled interval in the following manner: engage the drill rig clutch and, in the lowest forward gear possible, turn the rod two full turns. This should break the sample off at the leading cutting edge of the sampler, and the sampler can then be returned to the surface for removal and handling. Note: The thin-wall Shelby-tube sampler has no core-retaining device; it relies on friction and the rubber-seated ball check to provide a vacuum for holding the sample. When the Shelby-tube sampler is used for sampling materials too dense to push or thrust with the sampler to full penetration, a drive hammer can be used (as described in the discussion of the drive-coring method). Very light hammer blows need to be used because the thin-wall (0.065 in.) construction of the Shelby tubing can withstand very little abuse. In addition, any small gravel encountered by the sharpened, very thin cutting edge of the tube will result in its being distorted and will probably disturb any additional material entering the tube. By driving the sampler into the formation instead of pushing it in, vibrations are created that result in some sample disturbances.

After the sampler is carefully tripped out of the hole, the Shelby tube, containing the undisturbed sample, is removed. This is done by removing the tube retaining screws (fig. 26) from the sampler head. The ends of the tube are then plugged with thin discs of either steel or brass (discs are slightly smaller than the inside diameter of the Shelby tube). Sealing wax, cheesecloth, and tape are then applied over the disc-plugged ends.

Solid-Stem Auger Sampling in Saturated Materials

The primary problem with drilling in loosely consolidated, saturated materials is collapse and filling of the hole as the augers are removed. Methods for cleaning out an auger hole above the water table will not work in this case, because whatever materials are removed will simply be replaced by additional saturated material. Therefore, the methods for obtaining representative core samples in this environment are restrictive and laborious. However, there are times when a sample need is great enough to justify that effort. An example is a situation where installation of an observation well is necessary in a clean sand bed, but, because of the badly contaminated cutting samples brought to the surface by the auger flights, the type of aquifer material penetrated is questionable. A drive-core sample can be obtained *in this situation* by removing the augers very slowly while rotating them clockwise until they are above the saturated zone. Auger as much slough material as possible up the hole. After the augers have been removed from the hole, fasten the 3-in. solid- or split-barrel with the ball check removed to the N rod and lower it to within a few feet of the caved material; the thickness of fill-in needs to be determined after auger removal.

Next, fasten a water swivel to the top of the N rod and start pumping water through the rod and out the bottom of the sampler. As the sampler comes in contact with the caved material, increase the pumping rate to 25–30 gal/min, and jet the sampler down through the caved material. As the jetting or washing out of the caved material progresses, the returns may or may not flow out at the surface, depending on permeability of the hole wall. When the sampler has been washed to the bottom of the hole, the water swivel is removed; the drive hammer is attached; and the sampler is driven into the formation of interest. Occasionally, when this method is used, settling out of suspended sediment makes dislodging the sampler from the penetrated formation difficult. If the sampler will not dislodge with the drill-rig winch or hydraulics, use the reverse drive-hammer method previously described.

Hollow-Stem Auger Sampling in Unsaturated Materials

Core sampling through the hollow-stem auger in unsaturated materials is a relatively simple process. Unlike the problems of loose material left in the hole when solid-stem augers are pulled, the hollow-stem auger remains in the ground to act as a casing and hold out any potential caving materials. The only loose material remaining in the hollow-stem auger-drilled hole is 2–3 in. of material loosened by the pilot bit, that has not been moved up the auger flight. The method for sampling through the hollow-stem auger (fig. 27) is: drill the augers to the prescribed sampling depth; stop rotation; remove the hollow-stem auger adaptor cap and center-rod bolt that holds the rod-to-cap adaptor to the hollow-stem auger-adaptor cap; remove the center rod-to-cap adaptor; fasten a swivel to the center rod; and remove the rod from the hole with the wire-line winch. After the center rod has been removed, unscrew the bottom 5-ft section of the center rod that has the pilot bit and center-assembly plug attached and lay it aside. Next, attach the sampler to be used to another 5-ft section of center rod;

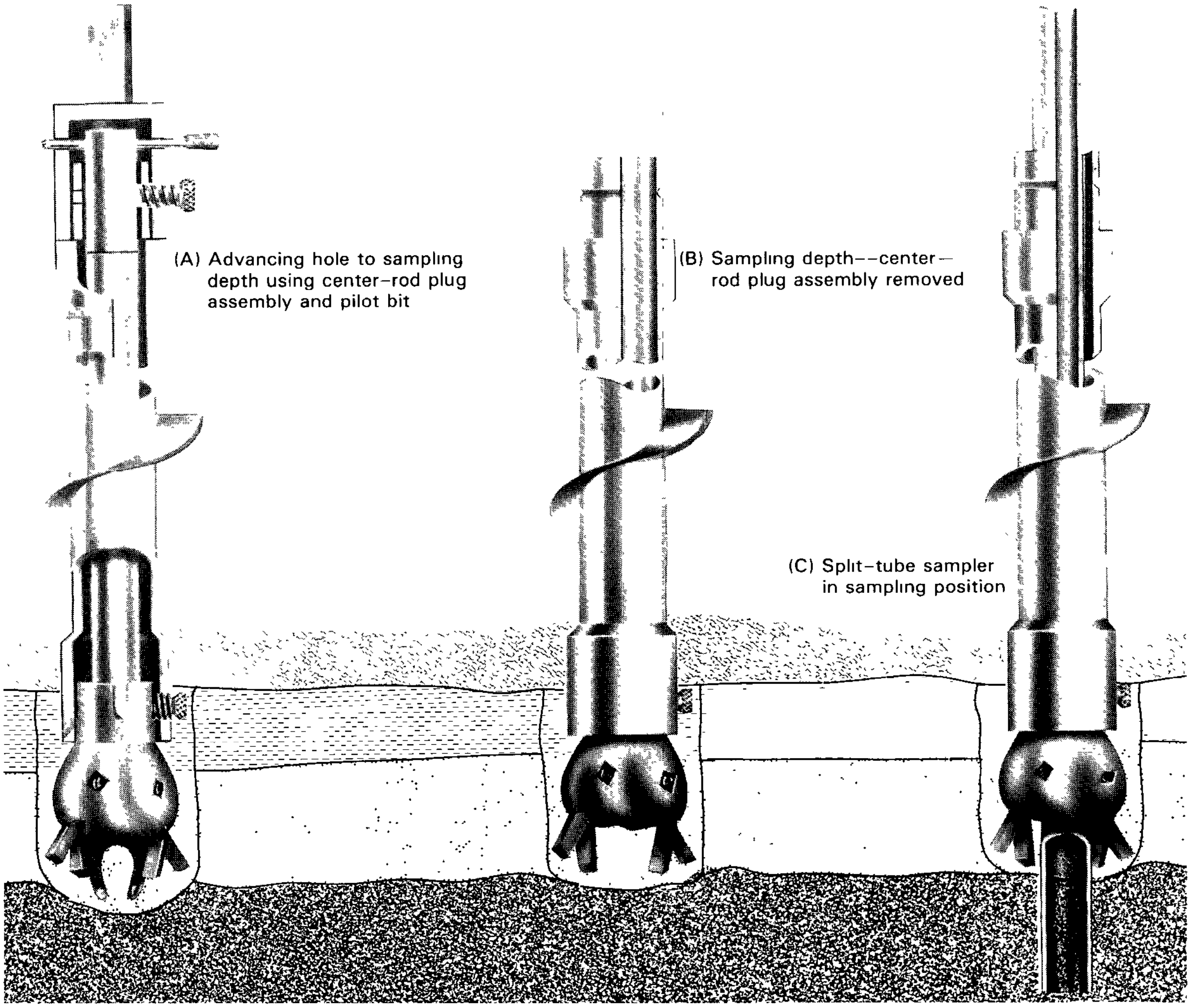


Figure 27.—Soil-sampling technique using hollow-stem augers and split-tube drive sampler.

reattach this section to the last section of center rod removed from the hollow-stem auger; and lower the entire string to the bottom of the hole in preparation for sampling.

The following procedures are guidelines to sampling. For example, when drilling in a formation containing sand, with possibly some fine gravel, and a sample is required, the 3-in. solid- or split-barrel sampler with three 6-in. aluminum liners may be used. Assuming that the sample barrel is set on the bottom of the hole, 20 in. is measured above the top of the hollow-stem auger and an easily distinguishable reference mark is made on the drive rods. The method for collecting the drive sample is the same as that described for solid-stem auger-drilled holes (page 50); all sampling methods described for solid-stem auger drilling are applicable to hollow-stem auger sampling. Note: When sampling is done through the hollow-stem auger, that is, when the center rod and pilot bit are removed, usually 2–3 in. of disturbed material remains from the drilling action of the pilot bit that has not been moved up the auger flights. After the sample has been collected and returned to the surface, the sampler has been dismantled, and the inner liners have been removed, the loose, contaminated material can be poured out of the upper 6-in. liner. However, in practice, the upper 6 in. of sample rarely is used except for general lithologic logging of the hole, because it is the part of the sample that will be the most disturbed and possibly contaminated. If removing these few inches of disturbed material prior to collecting the sample is necessary (for example, if collecting a full-length, undisturbed sample using a Shelby tube is necessary), a 3-in. drive-core barrel equipped with basket retainer could be run into the hole and driven a few inches into the undrilled formation. When the sampler is removed, the hole bottom will be clean for sampling.

Hollow-stem augers offer another method of coring not previously described: rotary coring through hollow-stem augers. For instance, if auger drilling or sampling is done in unconsolidated materials and a refusal point for auger drilling is reached and it is not known whether this may be just a boulder or bedrock, attach a standard NX size or similar rotary core barrel to the center rod, mix a drilling mud, and proceed with a standard hydraulic-rotary coring method, using the in-place hollow-stem auger as surface casing through the overburden. The augers will provide a return conduit for the drilling fluids and cuttings.

Hollow-Stem Auger Sampling in Saturated Materials

Core sampling through hollow-stem augers in saturated materials encounters problems that require different techniques than those described for the unsaturated zone. The greatest problem is piping. When the center-assembly plug and pilot bit are withdrawn, there is a tendency for the viscous slurry of cuttings, still contained in the bottom of the hole, to be pumped upward into the hollow-stem augers. Withdrawal of the center-plug assembly is analogous to a piston pump that pulls this viscous slurry into the augers. Before presenting coring methods through hollow-stem augers in the saturated zone, some methods to prevent piping from occurring and some remedial measures if it does occur are described in the following paragraphs.

When a required sampling depth has been reached below the water table, check to see if the center-assembly plug and the inner wall of the auger are sand locked together. If a sand lock or seal exists and the center-assembly plug can be pulled, a vacuum will be created at the bottom of the plug assembly that will pull the slurry or viscous sands in behind it. To verify the sand lock and to break it, remove the capscrew from the adaptor cap that fastens it to the top auger flight while leaving in place the center-rod bolt that couples the rod-to-cap adaptor. Now, exert a slow upward pull on the inner rod and move it up an inch to two, while observing the auger flights to see if they stay in place. If the augers start to move, a secure lock between the two can be broken loose by alternately pushing and lifting on the center-rod assembly. When the center rod is free, raise it just enough above the top auger flight to enable removal of the rod-to-cap adaptor. After removal of the adaptor, push the center rod back down until the pilot bit is at its original drilling depth; lower the hollow-stem auger adaptor cap back down to its original position; reinsert the threaded capscrew that couples it to the auger. Now proceed with the technique that will, in most cases, seal off the bottom of the hole and prevent slurried cuttings from moving up into the inside of the augers. Apply heavy down pressure to the hollow-stem and move the clutch just enough to thrust the auger head 3 or 4 in. into the previously uncut formation (the center rod and pilot bit will slide up without rotation because the rod-to-cap adaptor previously had been removed). As the auger is forced this short distance into the formation (using a minimum of rotation), a firm seal usually will be produced against the bottom of the auger head and the first auger whorl, which will prevent the slurried materials from breaking through. The pilot bit and center-assembly plug is withdrawn at a very slow rate to induce no pumping action. After the center-rod assembly has been removed sound the bottom of the hole to verify that the sealing technique was successful and that no large thickness of cuttings is in the bottom of the hole. There will be at least 3–4 in. of loose material in the hole as a result of from the pilot bit being pushed up in the sealing operation. If this thickness of material cannot be tolerated and handled in the manner previously described (pouring out or discarding the upper-contaminated portion of the sample), then a 3-in. clean-out barrel can be run in and the contaminated material can be removed prior to sampling.

Situations can occur where sealing off the hole (as described previously) is not successful. For example, when auger drilling into a viscous sand (which may be under artesian head and will flow into the hole during withdrawal of the assembly), then more involved remedial measures are needed, such as: 1. While auger drilling, keep the inside of the hollow stem filled with clean, prepared viscous drilling fluid (viscosity about 50-s). This fluid can be added as each auger is coupled by pouring from a standby barrel of mixed mud. During the auger-drilling operations, mud below the auger head is seldom lost because the natural tendency of drill materials is to move upward and close off the small annular space between the center-assembly plug and the wall of the hollow stem. This added fluid will not be lost through the joints of the auger, when using a screw-coupled auger or O rings between the joints of spine-coupled augers. Maybe less than one full column of drill fluid is required to prevent piping; prior drilling experience in the study area will usually dictate the fluid head needed in the hollow-stem auger to prevent this problem. 2. Another method of introducing viscous fluid into hollow-stem augers is to drill a ½-in. diameter outlet hole in the bottom section of the center rod (as close as possible to the top of the center-assembly plug), and pump fluid through the top in the center rod as needed. This technique is particularly helpful if a considerable amount of piping of the material is anticipated. Using this method, completely fill the hollow stem with whatever weight or viscosity of fluid is needed, while, at the same time, continuously pumping additional fluid into them to maintain full augers as the center rod and center-assembly plug is removed. Use caution in the speed at which the center-rod assembly is withdrawn. Withdrawing the rod at a rate that is too fast for the fluid to move down through the restricted (¼-in.) annular area between the inside wall of the hollow stem and the center-assembly plug will cause a vacuum at the bottom of the auger head, and loosely consolidated material will be pumped up the hole. These methods usually will keep any large quantity of contaminated material from entering the inside of the hollow-stem auger, and representative or undisturbed samples can be collected using any of the previously described methods.

Procedures of Sampling in Hydraulic-Rotary Drilling

As apparent from the discussion of mud and hole-control problems when the hydraulic-rotary system is used for drilling, taking representative samples of penetrated formations is difficult and relies on the skill and experience of the driller. We describe the normal collection of cuttings samples, as well as taking drive or push-core samples to provide more representative samples in a hydraulic-rotary drilled hole.

Samples from the Hole

The washing action of the drilling mud as it moves bit-generated cuttings up the borehole obviously is going to contaminate the samples to varying degrees. Even though there is a concentrated effort to maintain good mud control, some separation of particles will occur. Coarse particles will not be transported through the ascending mud as fast as medium or fine particles are transported, and these separations have to be recombined if a representative sample is to result. These problems are much more pronounced when drilling in unconsolidated materials. The principal concerns, when the mud-rotary method is used in drilling consolidated formations, are the ascending velocities of the mud and recombining of the samples from the drilled interval. Washing samples out of upper erodable formations will not be a problem.

Two common methods of collecting cuttings samples during the hydraulic-rotary drilling process are the following: 1. Samples are collected continuously (with a sieve, colander, or shovel) while drilling progresses. Samples collected by this method must be combined through the judgment of the driller or the person taking the sample. In this method, the ascending velocity of the mud carrying the cuttings to the surface must be considered (figs. 28 and 29). The velocities shown in the figures are based on the use of 2 3/8-in. and 2 7/8-in. drill pipe; any other diameter of drill pipe will change the annular area in the hole, resulting in a change of ascending mud velocity. 2. A deeper and wider section is cut in the ditch that carries the mud from the hole to the first major settling pit; this pit is referred to as the cuttings collector or temporary settling pit. As the mud flows through this first settling pit, its velocity slows and part of the cuttings drop out. The proper procedure for this method of sampling is to circulate the drilling mud with the string of drill pipe lifted slightly off the bottom of the hole, turning slowly until no cuttings are coming up with the mud (all cuttings are out of the hole). Now, clean out the temporary cuttings pit and drill a certain increment, maybe 5 ft; again, lift the bit off

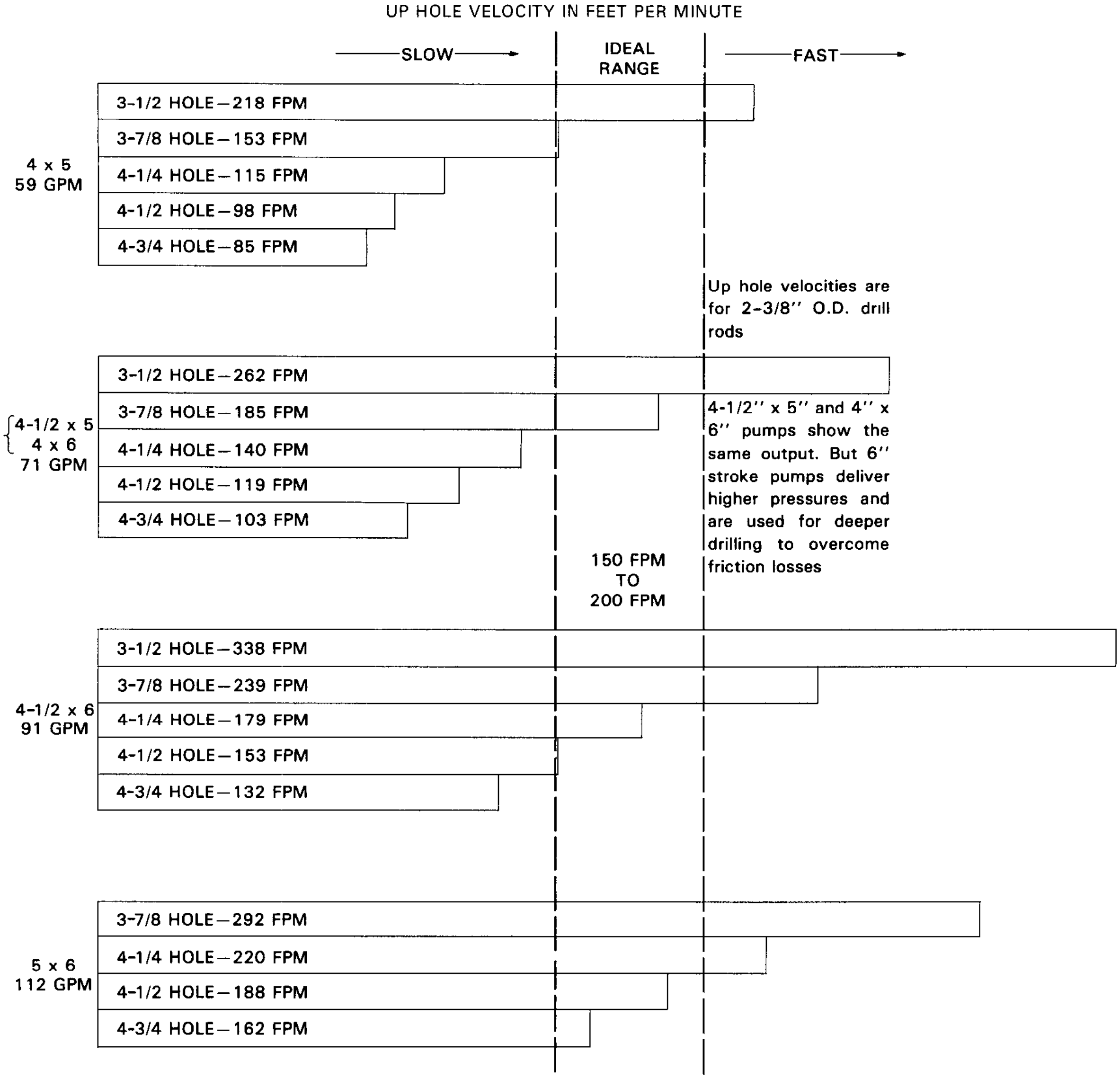


Figure 28.—Cuttings velocity.

the bottom and circulate until all cuttings are out of the hole. Cuttings that accumulate in the settling pit are placed in a bucket or tub and allowed to settle, later the excess fluid is poured off. This procedure is repeated for desired increments as the hole is deepened. The added time needed for drilling and circulating out all cuttings of successive increments is a slower method of sampling, particularly at greater depths; economics may dictate using the first method.

Whichever method of collection is used, it needs to be noted on the sample container and the sample bagged and correctly labeled after draining excessive fluid. These samples can be used later to construct a lithologic or geologic log of the formations penetrated by the drill bit. However, the geologist-hydrologist must rely on the driller's log or geophysical logs to construct the geological log because the driller's feel of the materials may result in a better lithologic log than using only the description of the cuttings.

Drive- or Push-Core Samples

The geologist-hydrologist too often relies on a mixture of cuttings to make critical decisions on the selection of screen-size openings and proper

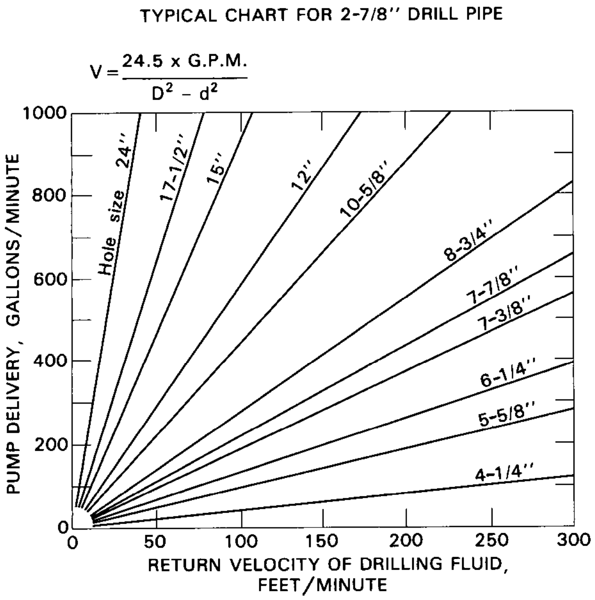


Figure 29.—Pump delivery versus return velocity.

placement of the screens. Also, obtaining an in-situ representative sample is sometimes necessary of the formations being sampled for chemicals or radionuclides and for samples taken for calibrating geophysical-logging tools and so forth. Drive-core sampling readily can be performed in hydraulic-rotary drilled holes; if proper mud control is maintained, contamination of the sample can be held to a minimum.

Variations for taking drive-core samples in a hydraulic-rotary-drilled hole ensure a relatively clean-bottom hole, and allow the driller to use his drill pipe rather than prescribed N rod as a push or drive rod. The procedure is: when the sampling depth is reached, the bit is lifted off bottom a few inches and the drilling mud is circulated until all cuttings that can be removed are removed from the hole. About 50 gal of a clean, high-yield bentonite drilling mud is prepared to a viscosity of between 50-s and 75-s. The drilling mud is then spotted in the bottom 25–50 ft of the hole. This spotting will provide a high-gel-strength drilling mud in the lower part of the hole that will prevent any sand or other cuttings from settling to the bottom. The string of drill pipe is then slowly removed from the hole to prevent swabbing (see p. 23 to 24). The drive-core barrel is now attached to the bottom of the string of drill pipe and run in the hole. Note: If any caved or bridged material is encountered, a description of the wash-in method beginning on page 71 can be used. However, no cuttings will settle through the previously spotted gel, in the bottom of the hole. The sample is then taken, using either the push or drive mode previously described. After the sampler has been removed and dismantled and the sample retainers removed, the sample is inspected to observe the amount of contamination resulting from the filter-cake invasion. If this sampling procedure is carefully followed, sample contamination will be very minimal except for the top 2 or 3 in. of the sample, which, if contaminated, can be discarded.

Shelby-Tube Samples

Sometimes, undisturbed, Shelby-tube samples may be required from a hydraulic-rotary drilled hole. The use of the Shelby-tube sampler is restricted, however, because the sampler cannot be washed in due to the ball-check valve in the sampler. The ball-check valve is needed in the head assembly of the sampler to retain the sample in the tube upon withdrawal of the sampler from the hole. To sample using the Shelby-tube sampler first spot the bottom several feet of the hole with the high-gel strength drilling mud. If any caving or bridging is anticipated when the string of drill pipe is to be removed from the hole, follow the procedure of circulating out of the hole as described on page 24. Otherwise, caved material will feed up into the sampler, resulting in bad or total contamination of the sample. After the Shelby-tube sampler has been returned to the surface, the upper few inches of contaminated material (filter cake, etc.) can be removed from the tube before sealing and waxing the ends of the Shelby tube.

Procedures of Sampling in Cable-Tool Percussion Drilling

Sampling Consolidated Materials

As mentioned previously, it is necessary to periodically bail the slurried cuttings out of the well. Contracts can specify bailing out of these cuttings at any desired interval (for example, every 5 ft or at any lithology change). Collect samples from the bail-out material; wash them if desired; geologically log them; and put them in a suitable container for future analysis. Although the sample chips are small, they are usually adequate for geologic and minerologic determinations when examined under a microscope. The drillers should be instructed to keep an accurate driller's log of the penetrated rock to complement the geologist's log. One reason for requiring this complementary log would be to note locations of voids or fractures that might have been encountered while drilling and would not be indicated in the cuttings but would have been entered in the driller's log.

Sampling Unconsolidated Materials

The method of collecting cable-tool cutting samples from holes drilled in unconsolidated materials is no different than collecting samples from hard-rock holes. However, if the driller is competent, his log interpretation of the drilled material must be heavily relied upon. For instance, examining the cuttings from a bailed-out section may indicate they came from a formation of dirty sand; however, the competent driller knows by feel and reaction of the drill bit that he actually drilled a gravel layer and a clay or silt-clay layer. The sample is a ground-up mixture of these layers; without the driller's-log input, an inaccurate lithologic log will be constructed.

Drive-Core Sampling

Hydrologists usually rely on a mixture of drill cutting samples bailed from the hole to determine the grain-size distribution of an aquifer material from which to select the proper screen-size-slot openings for constructing an observation well or production well. However, the cable-tool drill provides an easy method for determining the true grain-size distribution by means of drive-core sample analyses. Drive cores can easily be taken in dry materials or saturated materials with the cable-tool rig. After cuttings have been bailed out, fasten a drive-core barrel with inner liners and core retainer to the tool joint just below the drill jars (fig. 30). Lower the sampler to the bottom of the hole; make a mark on the drill line 20 in. above the casing or at some other reference point; and, by alternately lifting and dropping the jars, drive the sampler to the desired depth. After the sample has been driven, try to pull it out with the rig hoist; if it is too tightly anchored, use the jars in the driving mode for bumping it loose. Note:- When driving the sampler with the jars, do not raise the jars to the end of the slip-joint travel of the jars, or a direct upward blow will be imparted on the sampler, damaging the integrity of the sample. Using these jars for driving is contrary to their normal use; but, if the method is done carefully, no damage to the jars will result. This method provides a sample of the aquifer material that truly represents the grain-size distribution, not a mixture of materials drilled.

This same method can be used to take a relatively undisturbed core of cohesive soils, by using a Shelby-tube sampler. Use the lightest jars available and careful driving techniques to lessen the chance of disturbing the sample or even crumpling the thin-walled Shelby tube. In addition to collecting cuttings and core samples, the cable-tool method of drilling offers an excellent means of collecting water samples from the hole. This is especially true when drilling in unconsolidated materials, where the hole has been cased. Compacted materials behind the casing and on top of the casing drive shoe almost always prevent any water from moving down the hole; after cuttings have been removed and further bailing is performed to partly clear the water, water samples can be collected for analysis.

The cable-tool method can also be used to collect continuous, uncontaminated drive-core samples of unconsolidated material. This method of sampling could be used in areas where hollow-stem auger drilling cannot be contracted. This method was used by the Washington State District of the Water Resources Division of the U.S. Geological Survey for a study involving a TNT (trinitrotoluene) waste contamination. It was accomplished in the following manner: 1. A 4-in. drive-core barrel containing acetone-cleaned inner liners was driven 18 in. for the first sample, using drill jars as the hammer. 2. A section of 4-in. casing with a casing drive shoe was driven to the bottom of the sampled depth, and the 4-in. drive-core barrel was run inside the casing and driven to the original 18 in. to clean out the cuttings brought into the casing by the shaving action of the casing drive shoe. 3. After the cuttings were removed, the sampler containing new inner liners was again cleaned with acetone and another 18-in. sample was driven and removed. This sampling, driving of casing, cleanout of cuttings, sampler cleaning, and sampling again were done in several holes. As a comparison and evaluation of the

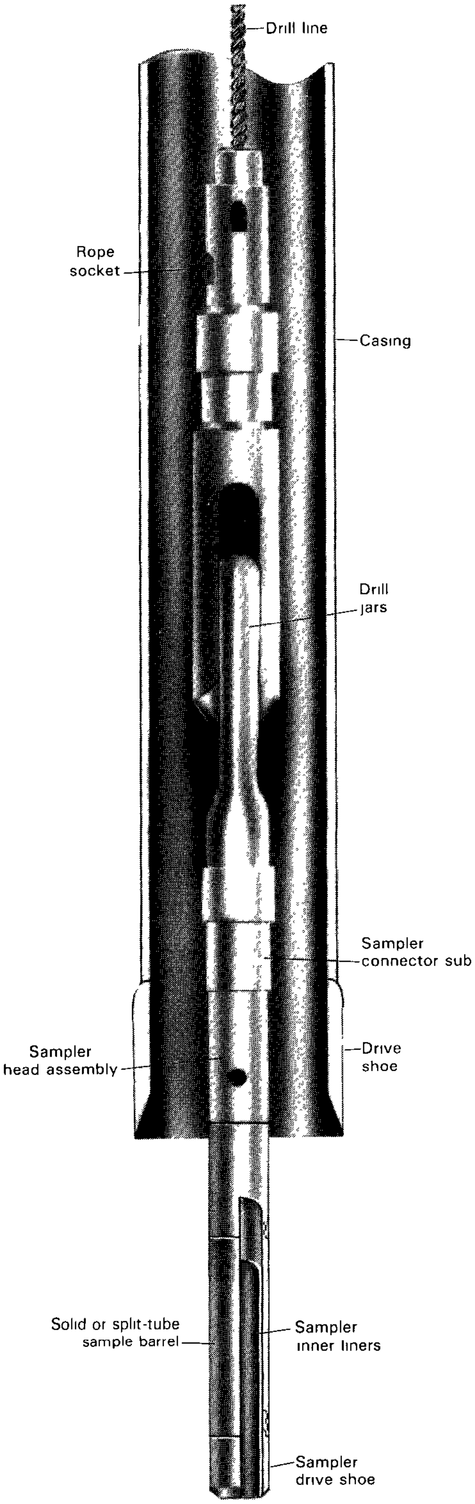


Figure 30.—Cable-tool drive-sampling apparatus.

method, a Water Resources Division auger-drilling rig used hollow-stem augers and drive-sampling equipment to sample one hole at the same location. Analytical results of the two methods compared favorably, but the hollow-stem-auger-drilling and drive-sampling method was several times faster than the cable-tool-drilling and drive-sampling method.

The method of cable-tool drilling and drive sampling was provided to show that there is another way of the sampling in this type of environment, if hollow-stem-auger-drilling and drive-sampling equipment is not available. Although this sampling was performed in unsaturated materials, it might also work for sampling below the water table if the Church method of driving and sealing behind the casing were used. Basically, the Church method utilizes a casing-drive larger in diameter than the diameter of the drive casing used to make an oversized hole. A drilling mud is pumped around the drive casing at the same time that it is being driven. The purpose of the drilling mud envelope is to lubricate the outside diameter of the drive casing while also maintaining a pressure seal around the casing and preventing upward artesian flow of water between the outside of the drive casing and the borehole annulus.

Procedures of Sampling in Air-Rotary Drilling

Procedures for sampling an air-rotary-drilled hole are essentially the same as those used for obtaining samples from a hole drilled by the hydraulic-rotary method. Drilled cuttings are collected from the return airstream using a sieve, colander, or shovel. Again, as with sampling the return cuttings from holes drilled by any of the other methods discussed, careful judgment must be exercised in logging the cuttings. Factors to be considered by the person taking the sample include: uphole- air velocity and lag time of returned-cuttings sample; sample mixing and balling as the cuttings are moved uphole in the return airstream (might contain mist, foam, polymers); periods of lost circulation and no cuttings return; and the competency and expertise of the driller to help assess the validity of the cuttings and depths from which they were drilled. In-situ sampling of materials using core barrels (air-rotary or drive-core type) can be taken anywhere in the hole if the driller is equipped with the necessary tools for doing so. If this type of sampling is done, standard- rotary air-coring techniques using dry air, foam, or mist would be applicable.

SAMPLING TOOLS AND THEIR APPLICATION

A sample may be defined as a representative unit or part of the formation penetrated in the borehole, that is obtained for purposes of analyses and description. Samples taken can be either disturbed (grab samples, drill cuttings) or undisturbed (samples obtained under in-situ conditions), depending on the techniques with which they are obtained from the borehole. In general, the less sample disturbance required, the more costly the method for obtaining the sample.

Sampling of soil and rock involves many engineering techniques and a variety of specialized downhole tools. These tools are generally referred to as samplers or core barrels; many of them are discussed in the following section.

Applications of Denison Sampler and Core Barrel

The Denison sampler and core barrel can be used to obtain excellent quality, relatively undisturbed cores of unconsolidated materials or consolidated materials. It can provide adequate cores for any laboratory analysis of hydrologic conditions, and it can obtain uncontaminated samples for waste-disposal studies. These results are only possible if the proper techniques and care are used in its operation.

The Denison sampler and core barrel (fig. 31), unique in design and versatility, is one of the best tools available for taking relatively undisturbed cores of soft or unconsolidated material. This device, similar to that of any double- or triple-tube core barrel can also be used to take cores of consolidated material, including hard rock, by adding the optional bottom coring assembly. The bottom assembly consists of an inner-barrel extension, split-ring core catcher, and bottom-discharge coring bit set with either carbide- or diamond-cutting edge. The unique design characteristics of the Denison sampler and core barrel do not offer any advantages over most double-tube core barrels when taking cores of hard materials; however, it is excellent for sampling soft material. The Denison sampler and core barrel comes in two standard lengths: 2 ft and 5 ft. For sampling mostly soft materials, the 2-ft barrel will give the best results.

The Denison sampler and core barrel is used in the following manner: in the soft-formation sampling mode, a preselected-length, boron-tipped (hard-surfacing material) cutter shoe with saw-toothed edge is attached to the bottom of the outer barrel. Three different lengths of cutter shoes permit a lead extension of the inner barrel of from ½ in. to 3 in.; the length of the shoe selected depends on the hardness of the formation materials to be sampled (fig. 32). To obtain a sample, run the Denison sampler and core barrel into the hole and set it on the bottom; continually circulate a drilling fluid having a viscosity of about 50-s; and slowly rotate the Denison sampler and core barrel (not to exceed 100 r/min) while, at the same time, pushing the Denison sampler and core barrel downward at a steady rate. As the Denison sampler and core barrel is pushed downward, the cored sample is passed through the core retainer and into the thin-wall liners of the inner barrel. As the sample moves upward into the Denison sampler and core barrel, the drilling fluid remaining on top of the sample is vented to the low-pressure area on the outside of the core barrel through a disc valve, resulting in a minimum of resistance to the sample as it slides upward into the brass inner liner. After the full length of the sample has been cut, the downward push and rotation of the Denison sampler and core barrel is stopped, and the sample is withdrawn slowly from the hole. After the Denison sampler and core barrel has been removed from the hole, it is dismantled; the brass inner liner is removed and marked as to the top, bottom, depth, and any other necessary data; it is capped, and the ends are waxed, if moisture retention is important.

As previously mentioned, the Denison sampler and core barrel has three different lengths of cutting bits available that permit a ½-in. to 3-in. lead extension of the inner barrel. The variable length of the inner barrel ahead of the cutting bit provides a broad field of sampling application to the Denison sampler and core barrel; it is further described in

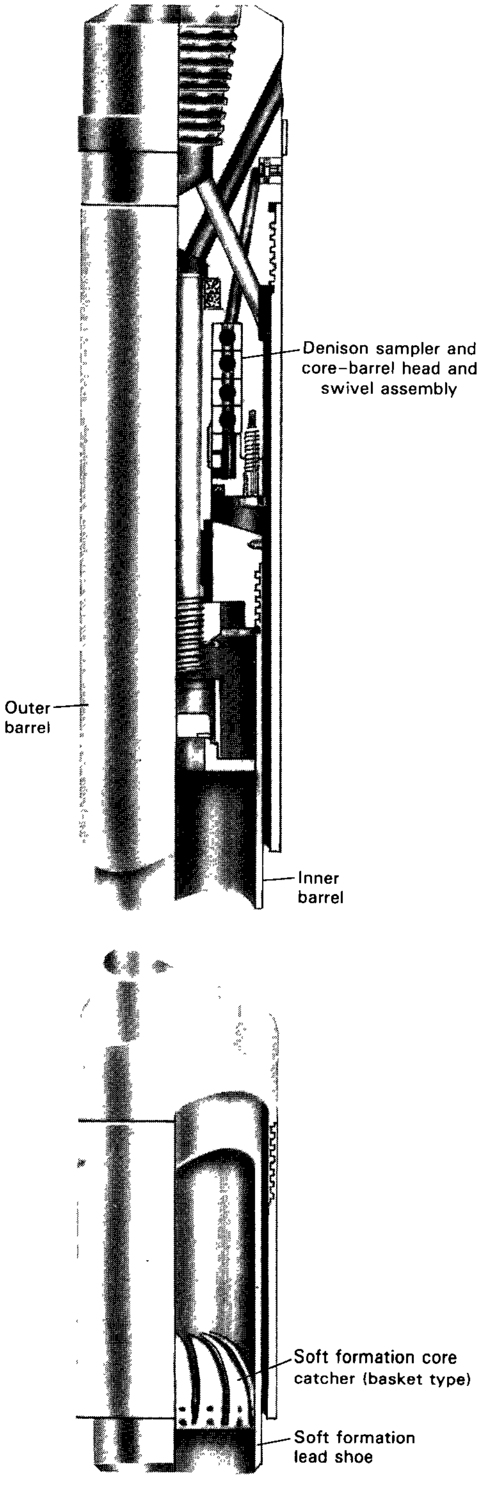


Figure 31.—Denison sampler and core barrel.

the following examples: in soft or loosely consolidated materials, a longer projection of the inner barrel ahead of the cutting bit is essential for best recovery, because the jetting or washing action of the drilling fluid would invade or wash away a loosely consolidated material if the discharge point of the drilling fluid was too close to that area of the material entering the inner barrel. In practice, use the longest inner-barrel extension that would still permit the downward movement of the Denison sampler and core barrel. In more consolidated material, a cutting bit close to the leading edge of the inner barrel may be essential to recover the core because the cored material is less compressible and not easily penetrated by the inner-barrel shoe. A cutting bit closer to the inner-barrel length is necessary to cut enough hole clearance for the downward progress of the Denison sampler and core barrel. Selection of the proper cutting bit to allow different lead lengths of the inner barrel must be learned by trial and error for the area and lithologic units that each user-operator is attempting to sample, but the overriding criterion for taking samples with the sampler is: use the longest inner-barrel extension possible to prevent invasion or fluid contamination of the sample. As much as 8,000 lb of downward thrust for a 4-in. O.D. Denison sampler and core barrel can be applied for penetration of the inner-barrel extension.

If sample materials are too dense or compact to be sampled by the previously described methods, then the Denison sampler and core barrel can be used as a standard core barrel by equipping it with the aforementioned optional bottom assembly for coring. The method of operation for coring hard materials with the Denison sampler and core barrel is no different than the methods of most double- or triple-tube core barrels. The Denison sampler and core barrel offers the advantage of conversion back to the soft-formation sampling mode, if the hard zones are only intermittent.

Removal of Sample-Retainer Liner from Inner Barrel

After the sample has been cut and retained in the brass inner liner, the Denison sampler and core barrel is slowly extracted from the hole and placed on a platform or set of sawhorses. Remove the core-barrel head and swivel assembly and inner barrel

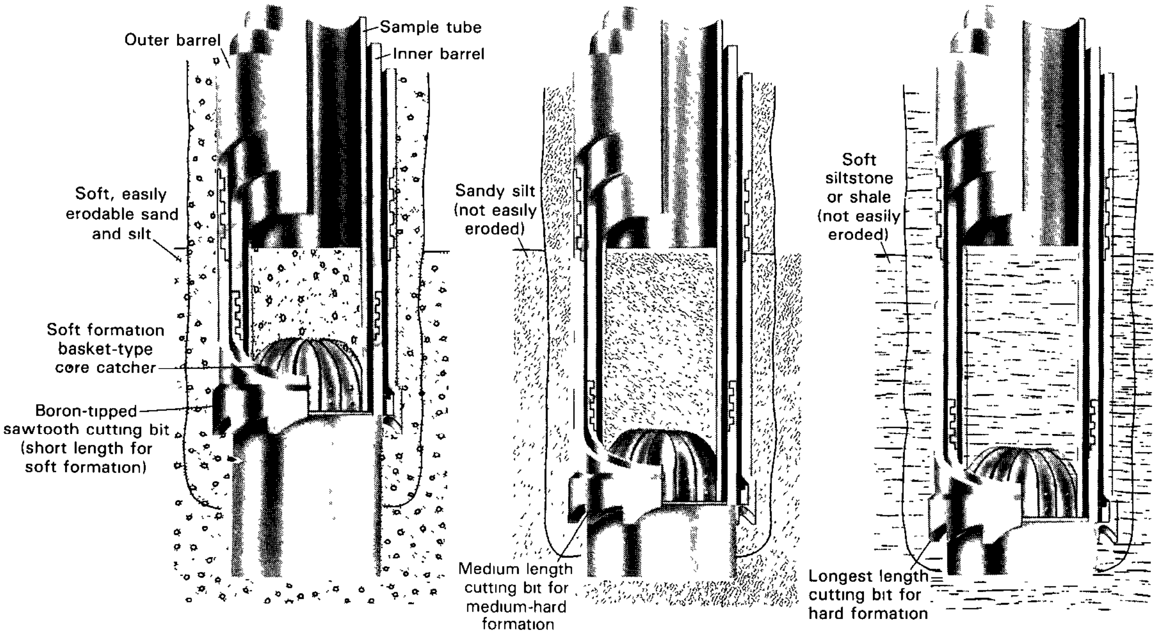


Figure 32.—Relationship of inner-barrel protrusion using different-length Denision-sampler cutting bits for drilling.

from the outer barrel. Strap the inner barrel into a pipe vise. Remove the inner-barrel lead shoe from the inner barrel; then extrude the brass inner liner. Under ideal conditions, the liner is withdrawn by taking hold of one end of the liner with a pair of vise grips or pliers while pushing on the other end with a short piece of the same-diameter brass liner. Occasionally, some fine grit gets in between the brass liner and the inner barrel, and this frictional locking of the inner liner makes it impossible to remove by hand. If this occurs, start the brass liner out of the inner barrel in the following manner. Place the inner barrel in a pipe vise, preferably mounted on the drill truck bed or bumper; place a short section of the same-diameter brass liner inside the inner barrel until it engages the shoulder of the brass liner. Then place the head of a mechanical or hydraulic jack against a block of wood that covers the open diameter of liner extension and place the base of the jack against an immovable backup; a slow, short-stroke operation of the jack will break the brass inner liner loose from the inner rrel and it can be readily removed. If the user anticipates a considerable amount of sampling with the Denison sampler and core barrel, it would be very advantageous to construct a simple type of extractor designed by the authors. The extractor (fig. 33) screws into the internal threads of the inner barrel, and turning the "T" handle the square-threaded push rod causes the sample-tube extractor ram to push the brass inner liner out of the inner barrel. We have never encountered any grit lock that could not be broken loose with this device. Note: Whatever system is used to start the brass inner liner out of the inner barrel, refrain from tapping or pounding on the sampler inner barrel, as not to damage the integrity of the sample.

Following are a few techniques that can result in good core recovery when using the Denison sampler and core barrel:

1. When pushing the inner barrel into the material being sampled, always rotate the outer barrel at a rate, less than 100 r/min. A fast rotation tends to set up vibrations that can destroy the integrity of a sample being pushed up into the inner barrel and inner liner.

2. Never use water as a drilling fluid (even though this is recommended in other literature), as there is far too great a chance for washing away the sample or invading ahead of the sample, resulting in a contaminated core. Use a lightweight but viscous drilling fluid having a minimum viscosity of 50-s.

3. When using the Denison sampler and core barrel as a sampler in soft formations, maintain a

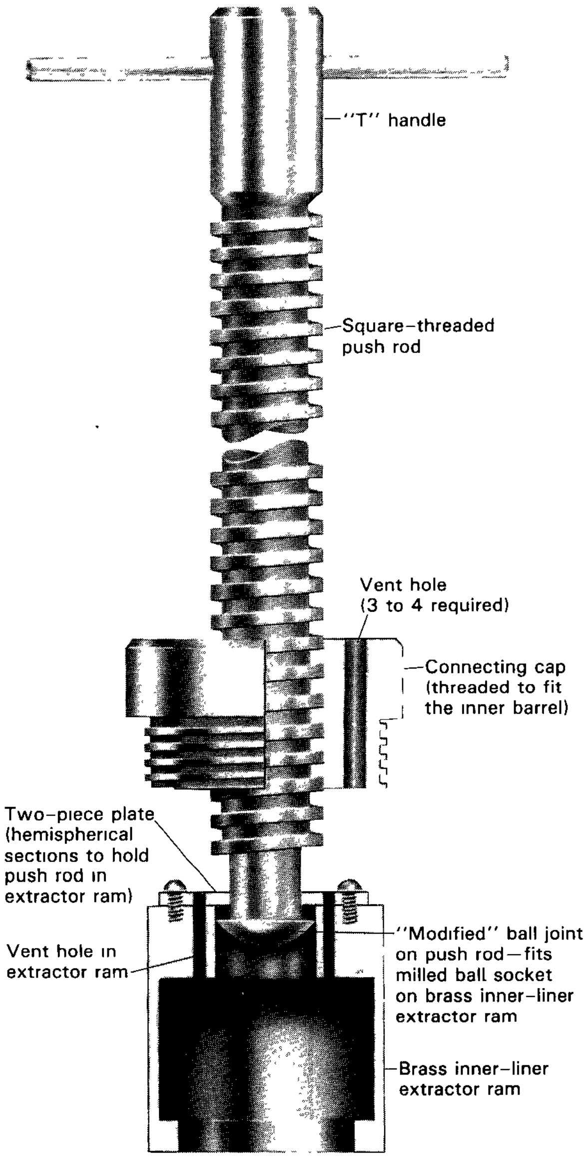


Figure 33.—Denison sampler and core-barrel brass inner-liner extruding assembly.

slow but steady rate of downward movement of the sampler. Do not progress the Denison sampler and core barrel faster than the drill fluid can carry the generated drill cuttings away from the cutting bit. If the sampler is pushed into the formation too fast, material that has not been moved up the hole will become jammed between the outer barrel and inner barrel, and it will cause the inner barrel to rotate with the outer barrel, shearing the bottom of the core off and disturbing any additional core that is pushed into the inner barrel. If the barrel locks together, return the Denison sampler and core barrel to the surface for cleaning and removal of core. Locking up the inner and outer barrel can be prevented by watching the drill-fluid pressure gage. For example: the sampler has been set on the bottom of the hole and the mud pump engaged; the pressure gage indicates a pressure of 50 lb/in.^{2} with a drilling-fluid discharge rate of 20–25 gal/min and coring of about 2 ft/min is begun, the cutting bit generates cuttings that must be removed from the hole and carried to the surface by the drilling fluid. This requires an additional 25 lb/in.^{2}. The pressure would then be about 75 lb/in.^{2}. As long as the pressure remains at about 75 lb/in.^{2}, coring is probably progressing satisfactorily. However, if the pressure approaches 100 lb/in.^{2} or more (caused by the cuttings not moving up the annulus fast enough or an invasion of sediment between the inner and outer barrel that is restricting flow), then the downward movement of the sampler should be slowed, not stopped, until the fluid pressure returns to about 75 lb/in.^{2}

4. As mentioned previously, the Denison sampler and core barrel comes in two standard lengths of 2 ft and 5 ft. If the material to be sampled is very soft, it is often better to take short coring runs (2 ft) so that there is no tendency to compress or distort the material in the inner liner. However, short coring runs can be accomplished using a 5-ft barrel as well as a 2-ft barrel, thereby still leaving the option of cutting a longer core if formations permit.

5. Shorter increments (standard is 5 ft) of the brass inner liners installed in the inner barrel may be preferred at times. This is possible but requires a particular note of caution. If five 1-ft brass inner liners, which are convenient for laboratory analysis, or two 2½-ft brass inner liners are preferred, the combination of lengths used must be cut full-length to ensure snug fit from shoulder to shoulder in the inner barrel; otherwise, grit lock between the brass inner liners and the inner barrel will occur at any separation, resulting in difficult brass inner-liner extraction.

Sampling Fluid Sands

Occasionally, the user of the Denison sampler and core barrel will encounter soft, fluid sands that will be lost through the slots of the basket retainer when the Denison sampler and core barrel is being removed from the hole. This loss of sample can usually be prevented by installing a sock of thin polyethylene sheeting around the basket retainer, before the retainer is installed in the lead shoe of the extension. The polyethylene sock should be long enough to cover the basket retainer and extend about 10 in. into the brass inner liner. The polyethylene should be slit longitudinally 1 in. apart several places about 4 in. from the top of the sock.

As the Denison sampler and core barrel penetrates the formation, the sand moves into the brass inner liners, past the basket retainer and polyethylene sock. When the sampling depth has been reached, downward movement and rotation of the Denison sampler and core barrel are stopped. Prior to removal of the Denison sampler and core barrel, allow a 2- or 3-min rest period so the cored fluid sands can settle and collapse the polyethylene sock over the fingers of the basket retainer. The Denison sampler and core barrel can then be withdrawn from the hole at a rate not exceeding 15 ft/min. A faster rate of withdrawal would cause undue suction on the bottom of the sample, resulting in its being lost in the hole.

The Denison sampler and core barrel is manufactured in four standard sizes: 3½-in. O.D., 4-in. O.D., 5½-in. O.D., and 7¾ in. O.D. Any of the four sizes recovers a relatively large sample in the inner nonrotating barrel and, because of these relatively large samples, usually causes less sample disturbance than is found in samples taken with smaller diameter sampling devices. Larger samples can be trimmed in the laboratory to minimize sample deformation caused by wall friction or slight drag of the core retainer springs on the sample. Sufficient sample volume exists to prepare several samples from any given horizontal strata.

Applications of Pitcher Sampler

The pitcher sampler can be used to obtain excellent-quality, relatively undisturbed cores of a variety of soil conditions. It can provide cores that are adequate for almost any laboratory analysis of hydrologic conditions as well as obtaining uncontaminated samples for waste-disposal studies. However, these results are only possible if the proper techniques and care are used in its operation.The pitcher sampler (fig. 34) was designed specifically to recover representative samples from formations that are too hard to be obtained using thin-walled Shelby samplers, or too brittle, soft, or water- sensitive to permit accurate recovery using conventional core-barrel-type samplers. It can provide uncontaminated samples of soft rock, sand, friable shales, and some clays that are too difficult to sample by other methods.

The pitcher sampler, like the Dension sampler and core barrel, offers the advantage of having a thin-walled Shelby tube extending below the point at which the drilling fluid is introduced, to remove drill cuttings from the hole. This feature prevents the drilling fluid from breaking through, eroding, or contaminating the sample, even in the softest materials. The mechanics of the inner-barrel extension of the Denison sampler and core barrel and the Shelby tube of the Pitcher sampler are quite different: the extension of the inner barrel of the Denison sampler and core barrel is predetermined by the selection of different-length cutting shoes installed on the outer barrel as explained beginning on page 63. Whereas the extension of the Shelby tube of the pitcher sampler is regulated by a high-tension spring within the upper core-barrel body (fig. 34), the Shelby tube of the pitcher sampler may extend as much as 6 in. ahead of the sawtooth bit and drill-fluid outlet (fig. 35A) when samples are taken of very soft or low-density formation. As the formation being sampled becomes harder and more difficult to penetrate, the upper housing of the inner assembly pushes up against the high-tension spring, which, in turn, exerts an ever-increasing thrust to the Shelby tube (fig. 35B).

The pitcher sampler is manufactured in several diameters ranging from 4½-in. O.D. to 7¾-in. O.D., which takes core samples from about 2¾ in. to 5 ⅞ in. in diameter. The standard pitcher sampler is the 4⅞-in. O.D., which takes a 3-in.-diameter sample. The pitcher sampler is also manufactured in two standard lengths, 5 ft and 3 ft. The 3-ft barrel is recommended to minimize disturbances of the material being pushed into the Shelby tube. In practice, the pitcher sampler is used in the following manner: the pitcher sampler is lowered into the hole on any of the standard drill rods. As the pitcher sampler is picked up and run into the hole, the 36-in., Shelby-tube liner will rest on the internal shoulder of the sawtooth bit and protrude about 30 in. below the sawtooth bit. This is a unique and advantageous feature of the pitcher sampler because it allows the drilling mud to be pumped directly through the Shelby tube and flush away any heavy mud or sediment debris that is in the bottom of the hole. As soon as the bottom end of the Shelby tube

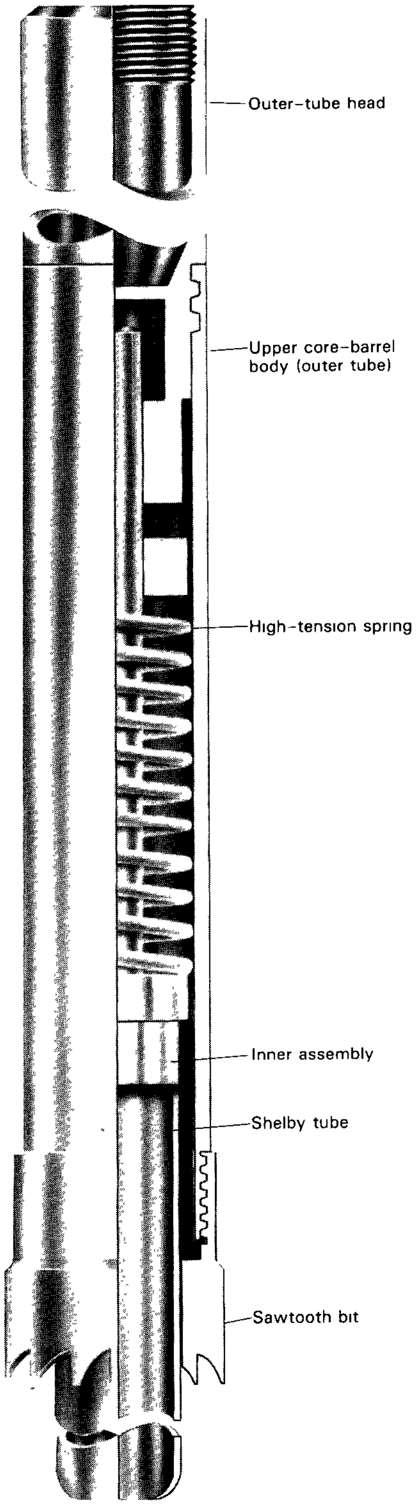


Figure 34.—Pitcher-sampler assembly.

meets any resistance of unsampled material, an internal sliding valve moves up, cutting off the supply of drilling mud to the Shelby tube and diverting it to the annular area between the Shelby tube and the outer tube. This fluid will then divert out the bottom of the sawtooth bit and transport the drill cuttings up the hole (fig. 35A and B). Drilling operations and sampling techniques are basically the same as those described for the Denison sampler and core barrel. Rotate the outer tube slowly to minimize any vibration that would disturb the cored material. Drilling-fluid discharge rate should be as low as possible but still carry the drilled cuttings up the hole. After the pitcher sampler has been pushed to full sample-penetration depth (3 ft) or to a point of refusal, the pitcher sampler is pulled out of the hole and the Shelby tube containing the sample is removed.

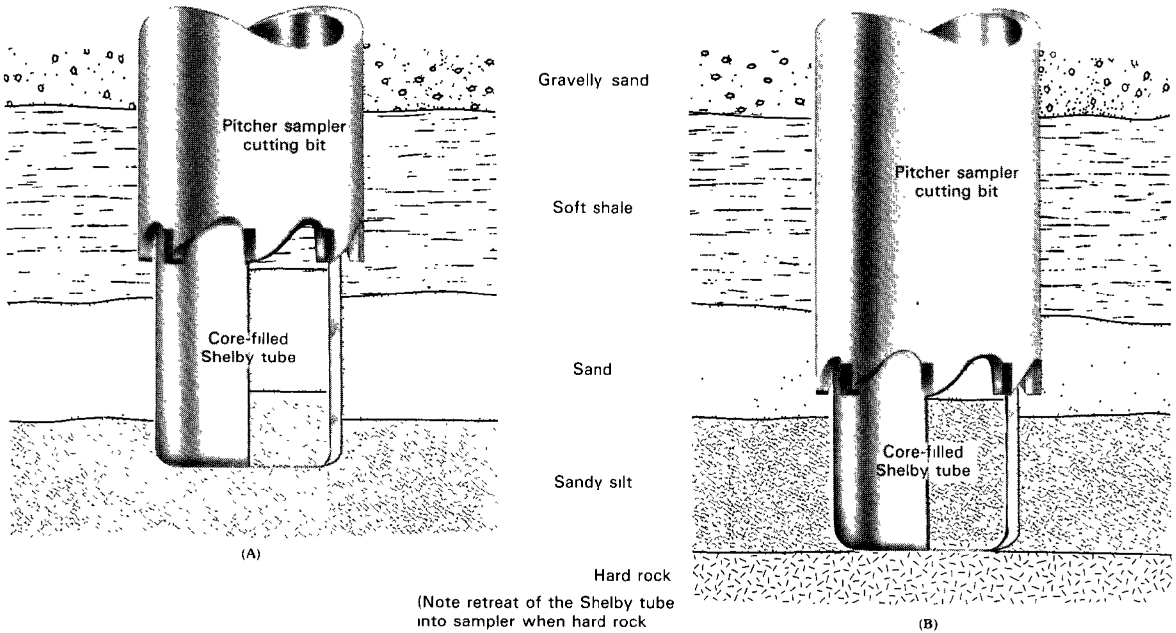
Removal of Shelby-Tube Sample Retainer

Removal of the Shelby-tube sample retainer from the pitcher sampler is a very simple operation. Unlike the Denison sampler and core barrel, which requires dismantling of the entire core barrel assembly, the Shelby-tube sample retainer is removed by taking out two allen screws. The Shelby tube containing the sampled material can then be prepared in the same manner as described on pages 73–74 for protecting Shelby-tube samples for storage or transport.

Applications of Solid- or Split-Barrel Samplers

The solid- or split-barrel samplers are simple but very useful tools for obtaining representative samples of unconsolidated formations. They can be used in any type of drill hole.

The tools are used widely in the soils-engineering field for SPT (standard penetration test); the ASTM (American Society for Testing and Materials) has published standards for the use of the sampler. The method is designated as: D1586–67 and is quoted here to (1) show potential users of the method for performing SPTs and (2) indicate that much of our discussion of the use of drive-core samplers does not



(Note retreat of the Shelby tube into sampler when hard rock is encountered)

Figure 35.—Pitcher-sampler operation; *A*, soft formations, *B*, hard rock.

(nor is intended to) meet ASTM standards. The following is the standard set forth by the ASTM: Standard Method for Penetration Test and Split-Barrel Sampling of Soils

1. Scope

1.1 This method describes a procedure for using a split-barrel sampler to obtain representative samples of soil for identification purposes and other laboratory tests and to obtain a measure of the resistance of the soil to penetration of the sampler.

2. Apparatus

2.1 Drilling Equipment—Any drilling equipment shall be acceptable that provides a reasonably clean hole before insertion of the sampler to ensure that the penetration test is performed on undisturbed soil and that will permit the driving of the sampler to obtain the sample and pentration record in accordance with the procedure described in Section 3. To avoid “whips” under the blows of the hammer, it is recommended that the drill rod have a stiffness equal to or greater than the A-rod. An ’A’ rod is a hollow drill rod or “steel” having an outside diameter of 1 ⅝ in. (41.2 mm) and an inside diameter of 1 ⅛ in. (28.5 mm), through which the rotary motion of drilling is transferred from the drilling motor to the cutting bit. A stiffer drill rod is suggested for holes deeper than 50 ft (15 m). The hole shall be limited in dia- meter to between 2¼ and 6 in. (57.2 and 152 mm).

2.2 Split-Barrel Sampler—The drive shoe shall be of hardened steel and shall be replaced or repaired when it becomes dented or distorted. The coupling head shall have four ½-in. (12.7 mm) (minimum diameter) vent ports and shall contain a ball check valve. If sizes other than the 2-in. (50.8 mm) sampler are permitted, the size shall be conspicuously noted on all penetration records.

2.3 Drive Weight Assembly—The assembly shall consist of a 140-lb (63.5-kg) weight, a driving head, and a guide permitting a free fall of 30 in. (0.76 m). Special precautions shall be taken to ensure that the energy of the falling weight is not reduced by friction between the drive weight and the guides.

2.4 Accessory Equipment—Labels, data sheets, sample jars, paraffin, and other necessary supplies should accompany the sampling equipment.

3. Procedure

3.1 Clear out the hole to sampling elevation using equipment that will ensure that the material to be sampled is not disturbed by the operation. In saturated sands and silts, withdraw the drill bit slowly to prevent loosening of the soil around the hole. Maintain the water level in the hole at or above ground-water level.

3.2 In no case shall a bottom-discharge bit be permitted. (Side- discharge bits are permissible). The process of jetting through an open-tube sampler and then sampling when the desired depth is reached shall not be permitted. Where casing is used, it may not be driven below sampling elevation. Record any loss of circulation or excess pressure in drilling fluid during advancing of holes.

3.3 With the sampler resting on the bottom of the hole, drive the sampler with blows from the 140-lb (63.5-kg) hammer falling 30 in. (0.76 m) until either 18 in. (0.4 m) have been penetrated or 100 blows have been applied.

3.4 Repeat this operation at intervals not longer than 5 ft (1.5 m) in homogeneous strata and at every change of strata.

3.5 Record the number of blows required to effect each 6 in. (0.15 m) of penetration or fractions thereof. The first 6 in. (0.15 m) is considered to be a seating drive. The number of blows required for the second and third 6 in. (0.15 m) of penetration added is termed the penetration resistance, N. If the sampler is driven less than 18 in. (0.45 m), the penetration resistance is that for the last 1 ft (0.30 m) of penetration (if less than 1 ft (0.30 m) is penetrated, the logs shall state the number of blows and the fraction of 1 ft (0.30 m) penetrated).

3.6 Bring the sampler to the surface and open. Describe carefully typical samples of soils recovered as to composition, structure, consistency, color, and condition; then put into jars without ramming. Seal them with wax or hermetically seal to prevent evaporation of the soil moisture. Affix labels to the jar or make notations on the covers (or both) bearing job designation, boring numer, sample number, depth penetration record, and length of recovery. Protect samples against extreme temperature changes.

4. Report

4.1 Data obtained in borings shall be recorded in the field and shall include the following:

4.1.1 Name and location of job,
4.1.2 Date of boring—start, finish,
4.1.3 Boring number and coordinate, if available,
4.1.4 Surface elevation, if available,
4.1.5 Sample number and depth,
4.1.6 Method of advancing sampler, penetration and recovery lengths,
4.1.7 Type and size of sampler,
4.1.8 Description of soil,
4.1.9 Thickness of layer,
4.1.10 Depth to water surface; to loss of water; to artesian head; time at which reading was made,
4.1.11 Type and make of machine,
4.1.12 Size of casing, depth of cased hole,
4.1.13 Number of blows per 6 in. (0.15 m).
4.1.14 Names of crewmen, and
4.1.15 Weather, remarks.

Deviations from ASTM Standards

Obviously the U.S. Geological Survey does not comply with the ASTM standards (use of different-size barrels, washing-in the sampler through caved material, using different drive rod, and so forth). These deviations are used to obtain representative samples of materials that will aid in the recovery of hydrogeologic data under less than ideal conditions. When possible, similar standards for collecting samples by the various available techniques are followed. However, the responsibility for collecting data to provide subsurface information needed to make critical decisions pertaining to water supply, contamination of water supplies resulting from solid-, chemical-, radioactive- (both solid and liquid) waste storage and disposal must be taken into account. To obtain the type of samples necessary to provide input of needed data for these studies, some accepted engineering standards must be modified or disregarded. Use whatever method is available for data collection, without undue concern about damaging sampling tools but with close attention to obtaining uncontaminated samples to provide vitally needed data.

Method for Drive Sampling

Although a specific description of drive sampling is provided in each of the drilling methods discussed in this manual, this general description is provided so the reader can refer to that particular section in the manual on the drilling method best suited to any particular sampling needs.pparatus

Apparatus

Solid- and split-barrel samplers are manufactured in a variety of diameters and lengths; our standard is

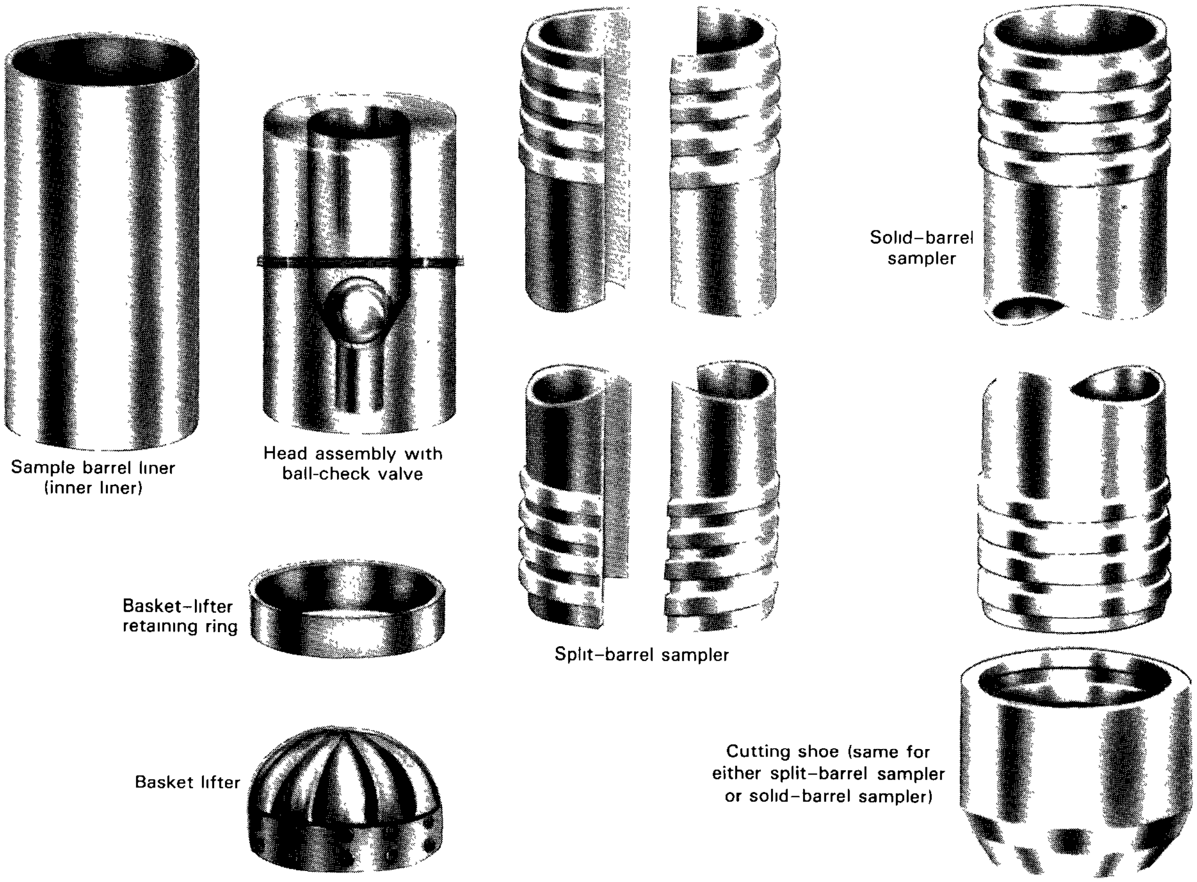


Figure 36.—Split-barrel sampler and a solid-barrel sampler with component parts.

a 3-in.-diameter, 18-in.-length sampler equipped with liners for retention and protection of the sample (fig. 36). The U.S. Geological Survey almost always uses N rod for drive rod instead of the A rod described in the ASTM standard because of needs to sample to depths of as much as several hundred feet rather than to the much shallower depths usually typical of soil-engineering studies. A 300-lb drive hammer rather then a 140-lb drive hammer is used to sample dense materials because much of the drive impact of the 140-lb hammer is lost in the whip and give of the lighter A rod, resulting in an insufficient blow to drive the sampler into dense material.

Procedure

Assume a clean-bottom auger-drilled hole that has had the cuttings removed or a rotary-drilled hole where cuttings have been flushed out and the hole spotted with a viscous, clean drilling mud to prevent downward penetration of fluid that would result in contamination of the drive sample. After the hole has been spotted with the drilling mud, follow the technique explained on pages 51 to 53 for driving the sample. The user must be aware that continued attempts to drive sample in a material that is very dense and hard (siltstone, sandstone, boulders, and so forth) will damage the sampler or break it off in the hole. A choice must be made concerning the ability of the sampler to absorb abuse versus the need for the sample.

Prior to obtaining a drive-core sample from a hole containing considerable cuttings or caved material, flush the material out and condition the hole with drilling mud in order to have a clean hole bottom for sampling. However, there are times when the sampler will have to be washed to the bottom of the hole because heavy cuttings settle out in the bottom of the hole or in a solid-stem auger-drilled hole bridging occurs due to improper drilling-mud control. This is accomplished in the following manner: remove the ball check from the sampler; mix a clean, lightweight drilling mud having a viscosity of about 50-s; connect the sampler to the N rod and lower it into the hole to a point about 3 in. above the bridged zone or the cuttings at the bottom of hole and circulate the drilling mud for several minutes to get the cuttings out of the hole or into suspension in the drilling mud at some point up the hole. If proper mud control is exercised in cleaning the hole, fluid invasion of the sample could be as little as 1 or 2 in., even in highly permeable sands. Note: Only a prepared drilling mud should be used for the cleanout procedure, because using water alone would cause considerable sample invasion and jetting damage to the proposed sampled interval. After washing the sampler to the bottom of the hole and flushing the hole is completed, the water swivel is removed from the N rod; the drive hammer is attached; and the sample is driven according to the sample-driving procedure.

After the drive-core sample has been driven to the prescribed or refusal depth, it is removed from the hole in one of the following ways: (1) dislodge the sampler from the formation by pulling it with the rig winch or hydraulics and (2) if the winch or hydraulics will not dislodge the sampler, the drive hammer is used in the reverse mode to jar up on it. The latter method should only be applied when absolutely necessary, because it adds to the disturbance of the sample. As soon as the sampler has been dislodged to a point that it can be retrieved with the rig winch, use the winch to pull the sampler and N rod out of the hole.

After removing the sampler from the hole and placing it in a pipe vise, the cutting-shoe head assembly and inner liners containing the sampled material are removed from the barrel. If the sampler is a solid-barrel type, the liners containing the sample must be extruded from the barrel (fig. 36). If the sampler is the split-barrel type, one-half of the split barrel is removed; the liners are marked at the top and bottom of the sample; a sharp knife is used to sever the sample at the liner joint. The liners are then individually removed, capped, taped on each end and properly marked with all pertinent data. Wrapping the sample liners in aluminum foil and dipping them in wax will help prevent desiccation. Any sample material remaining in the cutting shoe or any part of the sample not used for analysis can be used for visual description of the lithology. Note any pertinent data (ease or difficulty in driving the sample, number of hammer blows needed, and so forth) in the log book for sample evaluation. Note: With drive-core sampling experience, the user will learn through experimentation whether a basket-lifter retainer is needed in the bottom of the sample barrel or not to keep the sample from falling out when the sample barrel is dislodged. Many materials, particularly some sands and gravels, maintain enough friction to remain in the barrel without using a basket-lifter retainer. Coring without using a basket-lifter retainer, if possible, gains two advantages: (1) less disturbance of the sample occurs as it enters the barrel and (2) material in the bottom liner is not lost when the basket-lifter retainer is removed.

Applications of the Thin-Walled Tube Sampler

The thin-walled sampler utilizes a Shelby tube and is used primarily for the collection of undisturbed soil samples of low-density materials. The tool has limited sampling applications because of the fragile nature of the Shelby tube. Misuse will damage the sampler.

The sampler (fig. 37) is manufactured in a variety of diameters and lengths, but the Water Resources Division of the U.S. Geological Survey considers the 3-in.-diameter, 36-in.-length Shelby tube a standard. ASTM has established a standard method for sampling with the thin-walled tube sampler; this method, from ASTM D1587–83, is paraphrased here.

Standard Practice for Thin-Walled Tube Sampling of Soils

1. Scope

1.1 This method covers a procedure for using a thin-walled metal tube to recover relatively undisturbed soil samples suitable for laboratory tests. It is a guide to more complete specifications to meet the needs of a particular job.

1.2 In general, two types of samplers use thin-walled tubes for sampling, namely, open-tube samplers and piston samplers. In general, piston

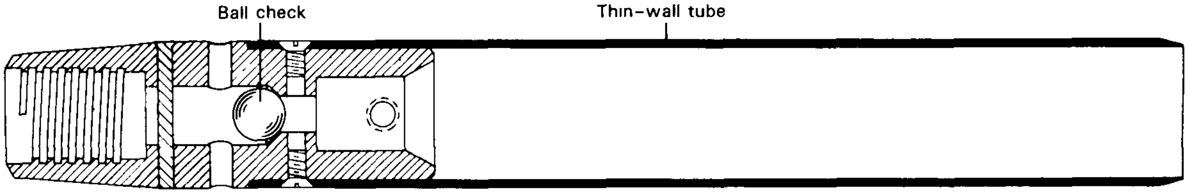


Figure 37.—Thin-walled tube sampler (Acker, 1974, reprinted by permission from Acker Drill Co., Inc.).

samplers are better and can be used in almost all soils. Since the thin-walled tube requirements are the same for both types of samplers, the method described applies equally to both.

2. Apparatus

2.1 Drilling Equipment—Any drilling equipment may be used that provides a reasonably clean hole before insertion of the thin-walled tube that does not disturb the soil to be sampled, and that can effect continuous and rapid penetration of the tube into the sampled soil.

2.2 Thin-Walled Tubes—Thin-walled tubes that are 2–5 in. (50.8-127 mm) in outside diameter and are made of any materials having adequate strength and resistance to corrosion will be satisfactory. Adequate resistance to corrosion can be provided by a suitable coating. Sizes other than these may be used, if specified.

2.2.1 Tubes shall be of such a length that 5–10 times the diameter is available for penetration into sands and 10–15 times the diameter is available for penetration into clays. Tubes shall be round and smooth, without bumps, dents, or scratches. They shall be clean and free from rust and dirt. Seamless or welded tubes are permissible, but welds must not project at the seam. The cutting edge shall be machined and shall be free of nicks. The inside clearance ratio shall be between 0.5–3 percent.

2.2.2 The coupling 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.

2.3 Sealing Wax—Any wax shall be permitted for sealing that does not have appreciable shrinkage or does not permit evaporation from the sample. Microcrystalline waxes are preferable to paraffin. Thin disks of steel or brass that are slightly smaller than the inside diameter of the tube are desirable for plugging both ends before sealing with wax. Cheesecloth and tape are needed. Suitable expanding packers may be used.

2.4 Accessory Equipment—Labels, data sheets, shipping containers, and other necessary supplies.

3. Procedure

3.1 Clean out the hole to sampling elevation using whatever method is preferred that will ensure that the material to be sampled is not disturbed. In saturated sands and silts, withdraw the drill bit slowly to prevent loosening of the soil around the hole. Maintain the water level in the hole at or above ground-water level.

3.2 The use of bottom discharge bits shall not be allowed but any side discharge bit is permitted. The procedure of jetting through an open- tube sampler to clean out the hole shall not be allowed.

3.3 With the sampling tube resting on the bottom of the hole and the water level in the boring at the ground-water level or above, push the tube into the soil by a continuous and rapid motion, without impact or twisting. In no case shall the tube be pushed farther than the length provided for the soil sample. Allow about 3 in. (75 mm) in the tube for cuttings and sludge.

3.4 When the soils are so hard that a pushing motion will not penetrate the sampler sufficiently for recovery and where recovery by pushing in sands is poor, use a driving hammer to drive the sampler. In such a case, record the weight, height, and number of blows. Before pulling the tube, turn it at least two revolutions to shear the sample off at the bottom.

3.5 Repeat the sampling procedures described at intervals not longer than 5 ft (1.5 m) in homogeneous strata and at every change of strata.

4. Preparation for Shipment

4.1 Upon removal of the sampler tube, measure the length of sample in the tube and also the length penetrated. Remove disturbed material in the upper end of the tube before applying wax and measure the length of sample again. After removing at least 1 in. (25 mm) of soil from the lower end and after inserting an impervious disk, seal both ends of the tube with wax applied in a way that will prevent wax from entering the sample. Where tubes are to be shipped some distance, tape the ends to prevent breakage of the seals. Place cheesecloth around the ends after sealing and dip the ends several times in the melted wax.

4.2 Affix labels to the tubes giving job designation, sample location, boring number, sample number, depth, penetration, and recovery length. Record a careful description of the soil, noting composition, structure consistency, color, and degree of moisture. Mark the tube and boring numbers in duplicate.

4.3 Do not allow tubes to freeze, and store them in a cool place out of the sun at all times. Ship samples protected with suitable resilient packing material to reduce shock, vibration, and disturbance.

4.4 Using soil removed from the ends of the tube, make a careful description giving composition, condition, color, and, if possible, structure and consistency.

5. Report

5.1 Data obtained in borings shall be recorded in the field and shall include the following:

5.1.1 Name and location of job,
5.1.2 Date of boring—start, finish,
5.1.3 Boring number and coordinate, if available,
5.1.4 Surface elevation, if available,
5.1.5 Sample number and depth,
5.1.6 Method of advancing sampler, penetration and recovery lengths,
5.1.7 Type and size of sampler,
5.1.8 Description of soil,
5.1.9 Thickness of layer,
5.1.10 Depth to water surface; to loss of water; to artesian head; time at which reading was made,
5.1.11 Type and make of machine,
5.1.12 Size of casing, depth of cased hole,
5.1.13 Names of crewmen, and
5.1.14 Weather, remarks.

The procedure used by the Water Resources Division of the U.S. Geological Survey for collecting thin-walled tube sampler samples does not deviate much from the standard set forth by ASTM. Some further suggestions for taking undisturbed thin-walled tube sampler samples not covered in the ASTM procedure are the following:

1. The thin-walled tube sampler is very fragile, and considerable damage to the sampler and distortion of the sharpened cutting edge can result when attempting to sample gravelly materials. If damage occurs, particularly if a part of the cutting edge is turned in, the damage will contribute to disturbance of any additional sample entering the tube. Therefore, stop sampling when gravelly materials are encountered. However, if the user is interested only in representative or geochemical samples of the material, then the sample can be forced or driven beyond its normal capacity. The Shelby tube may be ruined for future sampling purposes but a representative sample can be obtained.

2. The thin-walled tube sampler has no retainers for holding the sample in. The sample is held in the tube by the swelling of cohesive, sticky soils as it expands in the sample tube as well as the ball-check valve creating a vacuum on the sample. In practice, the cutting edge of the tube is rolled inward to provide an inside clearance of about 1 percent of the diameter. It is then reamed to provide a sharp cutting edge. The 1 percent restriction helps to hold the sample in the tube. It is often beneficial to let the sampler remain in the hole for about 15 minutes, after it has been pushed into the formation. This allows the soil to swell and provides an additional friction hold.

3. If a thin-walled tube sampler is used to collect a sample under saturated conditions and the sample is to be used for chemical analyses determinations, the hole should first be spotted prior to sampling with a clean, viscous drilling mud. Water should not be used instead of the drilling mud for this purpose because it would flush the chemicals out of the sampled material during the sampling procedure. The clean, viscous mud will provide good hole control, prevent caving, and minimize fluid invasion in the sample.

Applications of the Retractable-Plug Sampler

The retractable-plug sampler (fig. 38) is a lightweight coring device ordinarily used for shallow exploration studies and usually hand driven using a 25-lb slip hammer. The small diameter and fragility of this sampler prohibits its use for sampling very dense formations or for sampling beyond a depth of about 50 ft. The small diameter of the cores impose limits to their usefulness for the purpose of quantitative hydrologic analyses.

However, the retractable-plug sampler can take clean representative samples that are adequate for less quantitative hydrologic analyses, as well as chemical and waste-constituent analyses. The retractable-plug sampler is discussed because of its unique design with a retractable penetrating plug to prevent any material from entering the sampler until the retractable plug has been removed. This feature makes the retractable-plug sampler an excellent tool for collecting uncontaminated cores in a known waste or contaminated environment, assuming of course that the lithology and depth requirements fit the limits of the sampler. The retractable-plug sampler also offers a means for taking uncontaminated horizontal samples below a shallow waste pit or trench, if an adjacent working pit is constructed.

The retractable-plug sampler consists of the following components: a cutting shoe, an outer-tube barrel that accepts six 1x6 in. brass inner liners, an inner retractable-plug assembly, and a mating inner-rod-to-outer-rod, fluted-thread assembly that permits locking of the retractable plug in either the penetration or coring position. In addition to these components of the retractable-plug sampler, additional 5-ft increments of both inner rods and outer tubes are needed to reach the intended sampling depth, a drive hammer, a special drive section of the outer tube (do not drive on threaded sections of the outer tube), and a small-diameter drive-sampler extractor jack similar to the one shown in figure 39. The actual coring procedure with the retractable- plug sampler is accomplished in the following manner:

1. Fill the outer-tube barrel with 1x6-in. brass inner liners and attach a cutting shoe on the bottom. Adjust retractable-plug section (with an inner rod attached) so that the cutting shoe is completely plugged (retractable plug in down or sample-penetration position). The sampler can now be driven to the desired depth of sampling by adding 5-ft lengths of outer tubes.

2. The retractable plug is removed so that the core can be taken by inserting enough inner rod to reach the inner-rod-to-outer-rod, fluted-thread section. Engage the threads by turning clockwise,

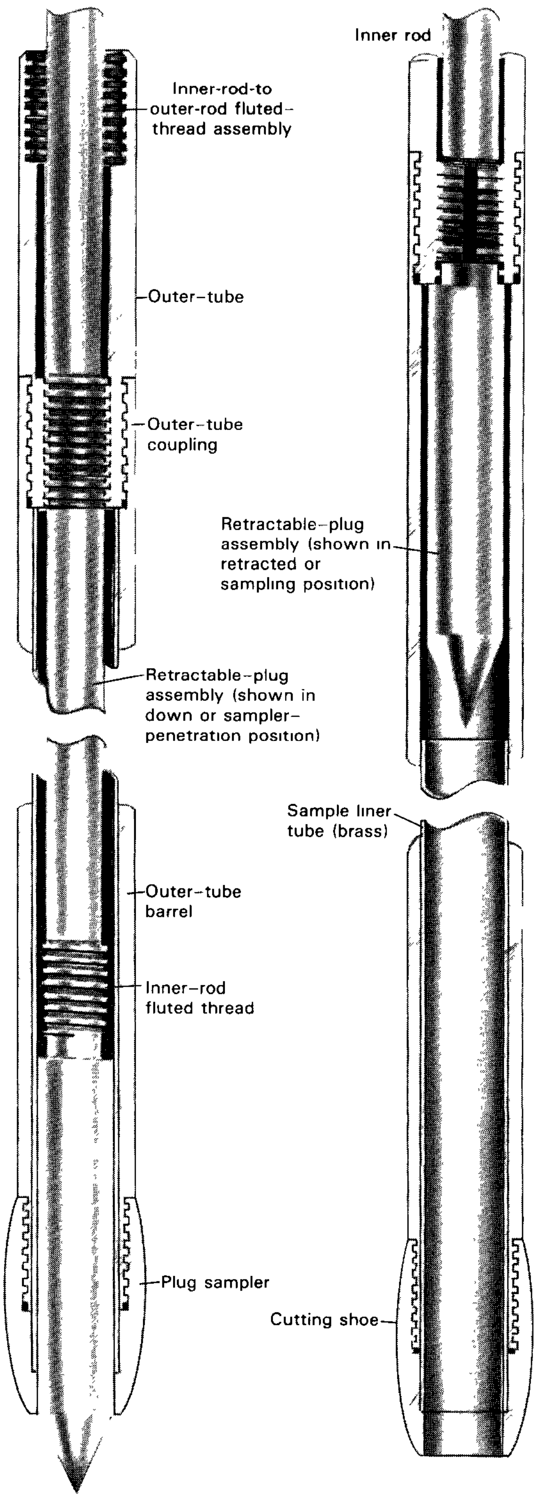


Figure 38.—Retractable-plug sampler.

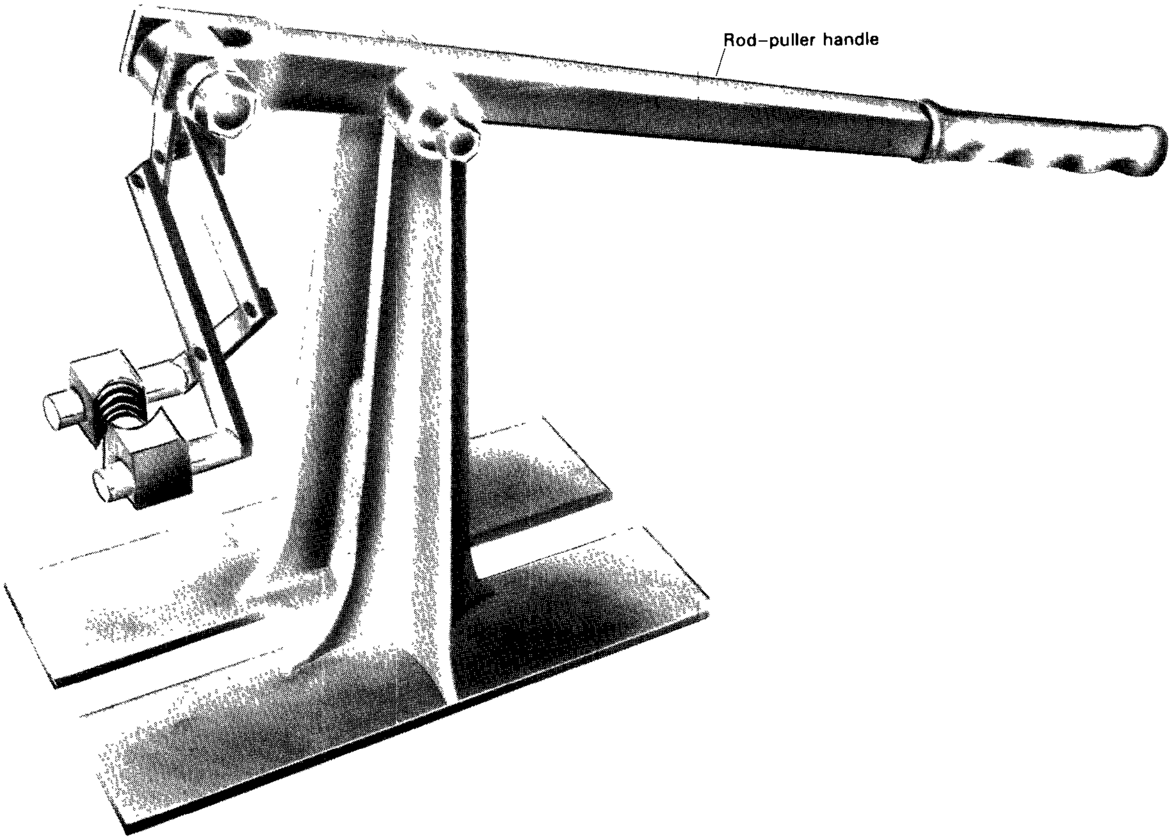


Figure 39.—Small-diameter drive-sampler extractor jack.

continue turning the inner rod (with small pipe wrench) until the upper fluted threads are free.

3. As soon as these threads are free, raise the inner rod with retractable- plug assembly attached until the bottom inner-rod fluted-thread section contacts the upper-thread housing; engage these threads about five or six turns by lifting up on the inner rod and turning it to the right (clockwise). Note: Do not make these threads up until they seat tightly, because the flutes in the threaded section are there to allow the upward escape of air (or fluid if it exists), when the core enters the barrel.

4. Remove the upper section of inner rod if it extrudes too far; attach the drive-head section of outer tube and use the slip hammer to drive the sampler about 2 ft.

5. After the sampler has been driven the 2 ft, remove the special drive section of the outer tube; reattach the top section of inner rod; and seal the sample in, by turning the inner rod clockwise, until the fluted-thread section is tightly seated. This creates a vacuum on the sample that holds it in the outer-tube barrel when the sampler is extracted, as well as keeping any possible fluid away from the sampled material. After a sample has been collected, prior to extraction, a pipe wrench is used to turn the outer tube two full turns clockwise to assure that the sample has been sheared at the bottom of the cutting shoe.

Extraction of the Sampler

Extract the retractable-plug sampler by one of the following methods:

1. Attach the small-diameter drive-sampler extractor jack (fig. 39) to the outer tube and thrust downward on the extractor-jack handle. Usually, after the sampler has been extracted 1 or 2 ft using the extractor jack, it can be pulled the rest of the way from the hole by hand.

2. If an extractor jack such as that described above will not pull the sampler, it can be extracted by fixing a fabricated rod-pulling clamp (fig. 40) to the

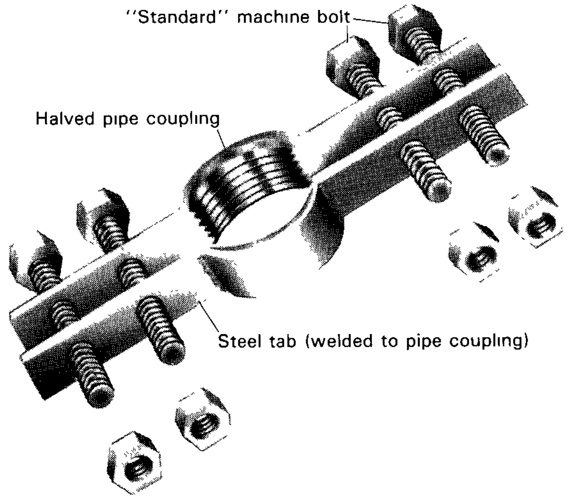


Figure 40.—Fabricated rod-pulling clamp.

outer tube about 1 ft above ground surface and (fig. 41) by using two hydraulic jacks (one under each flange of the clamp) to pull the sampler loose. Note: Do not use a single jack for this operation as it will bend the sampler outer tube. Use two jacks as described, and operate them simultaneously, in order to apply equal force to each flange of the clamp.

3. Some drive hammers used for driving the retractable-plug sampler are designed so that they can be used for driving the sampler upward to dislodge it. However, this is the least desirable method of extraction to use because a greater chance exists that vibration and shock will cause the sample to fall out of the outer-tube barrel.

After the sampler is dislodged, it is returned to the surface by alternately removing a 5-ft section of outer tube and inner rod. Prior to removal of the full sample-liner tubes from the outer-tube barrel, remove the cutting shoe and unscrew the outer-tube barrel from the retractable-plug assembly and remove it. The full sample-liner tubes can then be removed by one of the following methods:

1. Insert blank brass inner-liner tubes into the upper end of the outer-tube barrel and push the full sample liner tubes out of the bottom end of the outer-tube barrel. After the sample-filled inner-liner tube is extruded about 1 in., place a clean cap over the end of it and continue extruding it until the inner-liner tube is completely out of the outer-tube barrel; shear the end of the sample using a clean wire saw (ordinary cheese cutter is satisfactory) or a clean sharp knife. Cap the other end of the extruded liner. Tape both caps on with plastic, electrical tape and mark the sample properly with sample depth, hole number, top and bottom of sample, and any other pertinent data. Continue pushing additional blank inner liners into the outer-tube barrel until all of the sample-filled liners have been extruded, treating each individual sample as above.

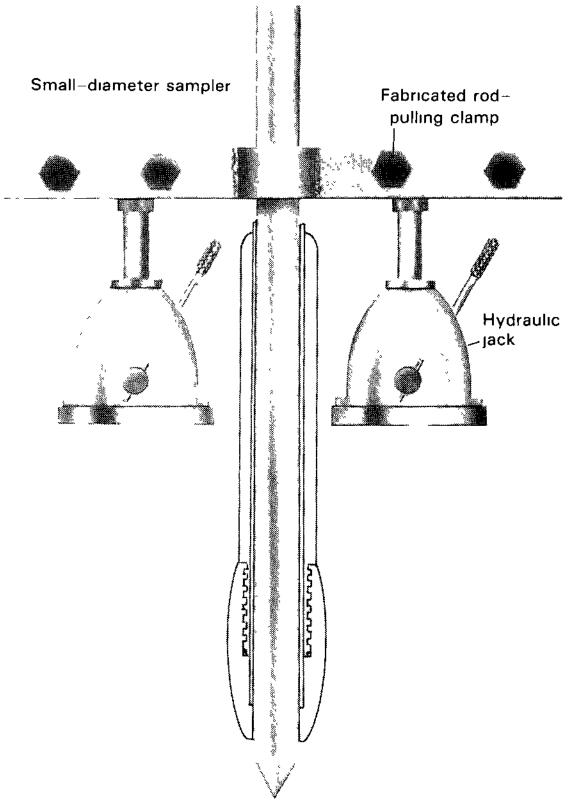


Figure 41.—Assembly for extraction of vertically or horizontally driven small-diameter sampler.

2. When sampling in saturated materials, some grit locking can occur between the inner-liner tubes and the outer-tube barrel, resulting in considerable difficulty in starting the inner-liner tubes out of the outer-tube barrel. For this reason, an inner-liner tube extractor assembly (fig. 42) designed by the authors should be used with the retractable-plug sampler. In operation, the sampler outer-tube barrel is locked to the extractor assembly by means of a chain-type pipe vise. A 1-in. plug that is swivel connected to a coarse-thread lead screw and fed through an internally threaded bracket welded to the channel-iron base of the extractor assembly butts against the inner-liner tube. Turning the handle

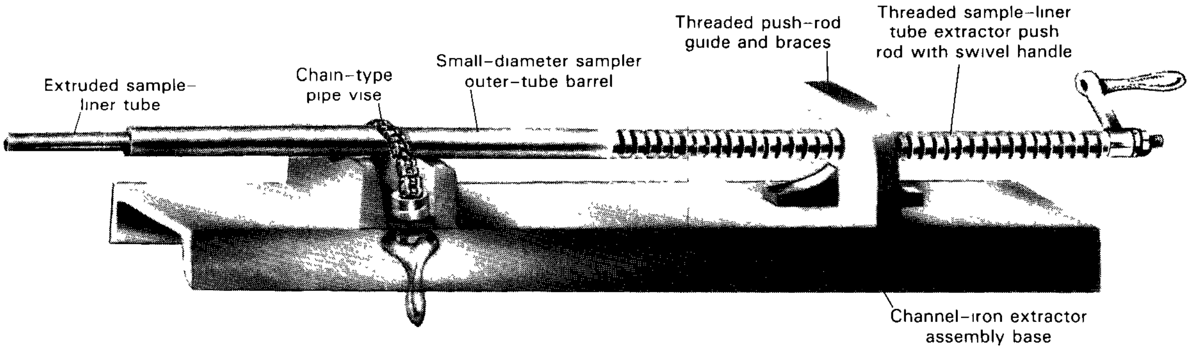


Figure 42.—Sample-liner tube extractor assembly.

clockwise forces the 1-in. plug against the inner-liner tubes, thereby breaking the grit lock and forcing the sample-filled inner liners out of the outer-tube barrel. Ordinarily, after two full inner-liner tubes have been extruded, the grit lock will no longer be a problem, and the remaining inner-liner tubes can be removed by hand. After the sample-filled liners have been removed and the outer-tube barrel is refilled with clean inner-liner tubes, the sampler is reassembled, and the sampling procedure is repeated.

Although the description of operation of the retractable-plug sampler emphasizes hand driving and removal, it is not intended to convey to the reader that the sampler cannot be used with power equipment, such as an auger-drilling rig, small drill rig, or even a tripod equipped with a cathead. Any power equipment makes it easier to collect samples, dislodge the sampler after sampling, and return it to the surface. However, this rather fragile sampling device cannot be treated like heavier duty drive-coring equipment. The retractable-plug sampler should not be driven with a drive hammer weighing more than 25 lb.

As mentioned previously this sampler offers a means for taking uncontaminated samples horizontally below a shallow waste pit or trench. This can be accomplished if an adjacent work pit is constructed to some depth greater than the waste pit to be sampled. The horizontal sample is obtained by driving the sampler as described for sampling in a vertical mode, the difference being that the sample is being driven horizontally. Dislodging the sampler for removal from the hole after sampling is somewhat different. The small-diameter drive-sampler extractor jack (fig. 24) is too heavy and awkward to position for use in horizontal extraction of the sampler. It can be extracted by using either extraction method 2 or 3, explained on page 223. If a considerable amount of horizontal sampling is anticipated, purchase (or have fabricated) a portable, double-acting hydraulic-jack apparatus. The ram must be well anchored, and it could provide the means for pushing the sampler into the material as well as dislodging it after collecting a sample.

If, for some reason, the work pit cannot be excavated to the necessary horizontal sampling depth adjacent to the waste-disposal pit to be sampled, samples can still be otained from beneath the waste-disposal pit in the following manner. Using a scale and a protractor, graphically construct a right triangle to determine the proper angle from the vertical and the necessary distance needed to drive the sampler to the predetermined sampling point below the bottom of the waste-disposal pit. Carefully begin driving the sampler from the predetermined angle and drive it the preselected distance below the bottom of the waste-disposal pit to collect the sample. Deviation of the sampler from the preselected angle usually does not exceed several degrees even if the sampler is driven a distance of about 50 ft.

Applications of the Stationary-Piston Sampler

The stationary-piston sampler (fig. 43) has been used very little for collecting samples for water-resource investigations because it is not capable of penetrating and sampling dense, coarse aquifer materials. However, the sampler offers the unique

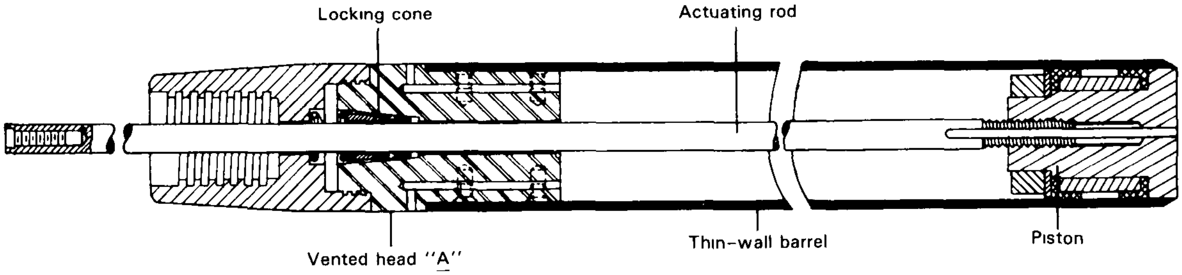


Figure 43.—Stationary-piston sampler (Acker, 1974, figure 77, reprinted by permission from Acker Drill Co., Inc.).

advantage of being completely sealed at the bottom, thus preventing any contamination of the sampler as it is lowered through fluid or cuttings in the hole. This feature warrants consideration of the stationary-piston sampler for use in known or suspected waste-contaminated environments, assuming that the formation to be sampled could be penetrated by the sampler.

In view of this potential, the following description in basic operation of the stationary-piston sampler (fig. 44) and the improved Lowe-Acker sampler (fig. 45) is provided (Acker, 1974, p. 69–71):

> The development of the Stationary Piston Sampler was a natural outgrowth of the use of the Thin-Wall Tube Sampler. As shown in figure 77, the construction of the Stationary Piston Sampler is similar to the Thin-Wall Tube Sampler except for the addition of a sealed piston and a locking cone in the head to prevent the piston from moving downward.
>
> By referring to figure 77, it can be readily seen that the Stationary Piston Sampler has two principal advantages: (1) It is fully sealed at the bottom so that it can be safely lowered through fluid and soft cuttings without fear of sample contamination; (2) by holding the piston stationary and pushing the sampler downward, the top of the sample is completely protected from any distorting pressure at the top. Thus, a much more effective vacuum seal is maintained than with the ball-check valve in the Thin-Wall Tube Sampler.
>
> Operation of the Stationary Piston Sampler: The hole is prepared in the same manner as it was for sampling with the Thin-Wall Tube Sampler. The Stationary Piston Sampler is placed on the bottom of the hole with the piston flush with the bottom end of the thin-wall sample tube. The actuating rod is held in place (see figure 78) and the sample tube is pushed past the stationary piston. The tube is then removed from the hole and separated from the sampler apparatus. The actuating rod (see figure 77) must be unscrewed a few turns, uncovering a vent hole to release the vacuum before the tube can be removed from the head. Once the tube has been removed, it is sealed and stored just like the thin wall tube sampler. In fact, once they are removed from the head, the thin wall tubes are identical and interchangeable).
>
> There are several variations of the standard Stationary Piston Sampler. The improved Lowe-Acker Stationary Piston-Plug Sampler shown in figure 79, is worthy of mention. This sampler represents an advance in both design and the use of improved materials. Standard size for this device is 3½ in. O.D. and is called the Modified 3½ in. Stationary Piston Plug Sampler.
>
> As the name implies, the improved sampler combines the features of the Plug-Type Sampler with the Stationary Piston Sampler so that the piston can be locked in the down location, it is possible to use the sampler without casing. Locking the piston in the top position ensures against movement after the sample is taken, thus insuring that the sample is not lost.
>
> This sampler also features a permanent steel barrel with plastic liner and a thin, elongated cutting shoe. The plastic liners that permanently retain the sample are tough, light, and inert. All in all, this is a more rugged, heavier-duty sampler than the thin-wall tube sampler or the standard stationary piston sampler. It is particularly useful in deeper sampling of heavy clays or where tidal or other conditions make it difficult to maintain casing.

SAMPLE CHARACTERISTICS

Undisturbed Samples

A considerable number of soil and rock samples collected each year by Water Resources Division personnel for hydrogeologic analyses and testing are

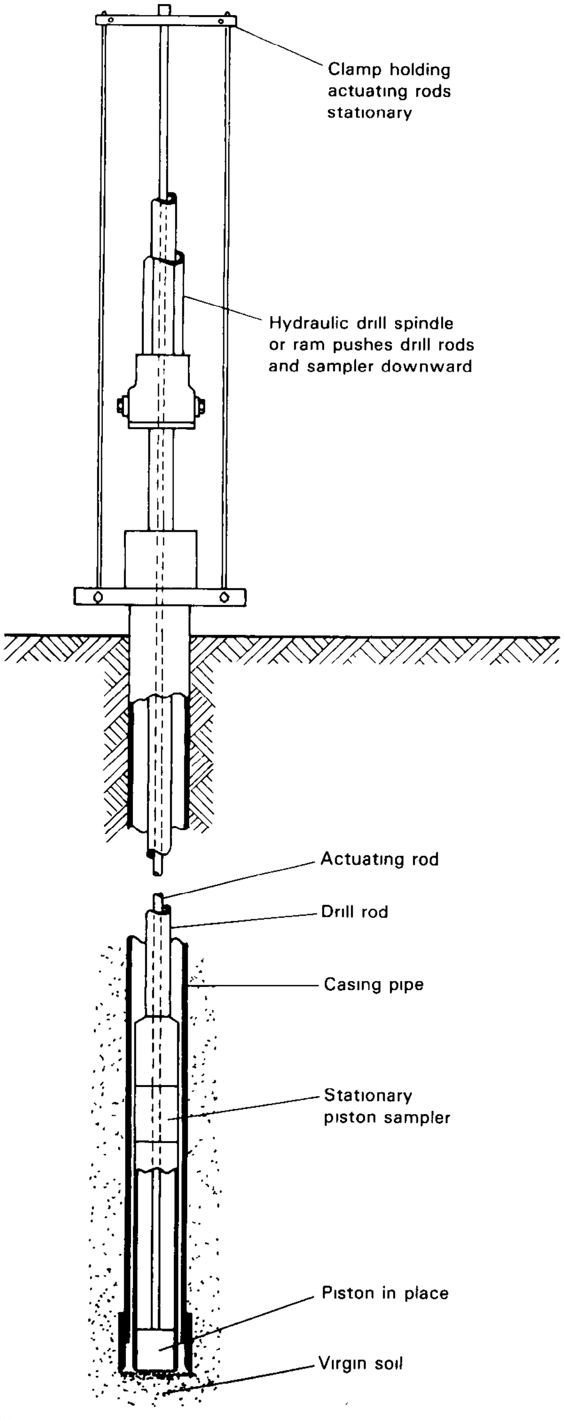


Figure 44.—Sampling operation using a stationary-piston sampler (Acker, 1974, figure 78, reprinted by permission from Acker Drill Co., Inc.).

found to be unsuitable for their intended uses. Causes of these deficiencies are often beyond the control of the sample collectors; however, in many instances, the failures result from an inadequate recognition of the relationship between sampling methods employed and the particular hydrologic tests required. The suggestions in this section provide information to enable onsite personnel to obtain samples with maximum efficiency and to better utilize laboratory-testing services. A considerable amount of the material in this section is from an unpublished manuscript, "Hydrologic Laboratory Note No. 7" (Edward A. Sammel, USGS, 1970).

Equipment

A prerequisite for undisturbed sampling in unconsolidatd materials is that the sample be collected and retained in a rigid tube in which the sample can also be shipped, stored, and subsequently mounted in a permeameter, if tests for hydraulic conductivity are desired. A thin-wall sampler, such as the Shelby tube, causes a minimum amount of disturbance, particularly in compressible sediments, and allows the sample to be tested in the sampling tube itself. However, for most sampling conditions, a thin-wall sampler will not support the stresses of hard driving, and other tools must be used. Double-tube samplers, in which the core is retained in an inner tube, represent a compromise between optimum sample conditions and the strength requirements imposed by most rock materials. Results obtained by using double-tube samplers are adequate for most purposes, if care is taken to minimize several problems discussed hereafter. Liners should be thin-wall, seamless tubing, with the ends smoothed, and should be cut perpendicular to the long axis of the tube. Because liners corrode rapidly during storage, the material should be corrosion resistant. Brass or corrosion-resistant steel have been preferred materials for liners, but their cost almost precludes their use on many projects. Tests of aluminum tubing have shown that it is relatively inexpensive and generally satisfactory, although some corrosion may occur during prolonged storage, and care must be taken to avoid flattening the tubes into oval cross sections.

Tubes of solid-fiberglass epoxy material were recently tested and found to have excellent properties of strength and rigidity. However, because they absorb and transmit significant amounts of water, they should not be used if determinations of moisture content are desired or if desiccation would impair the reliability of tests. Liners of laminated

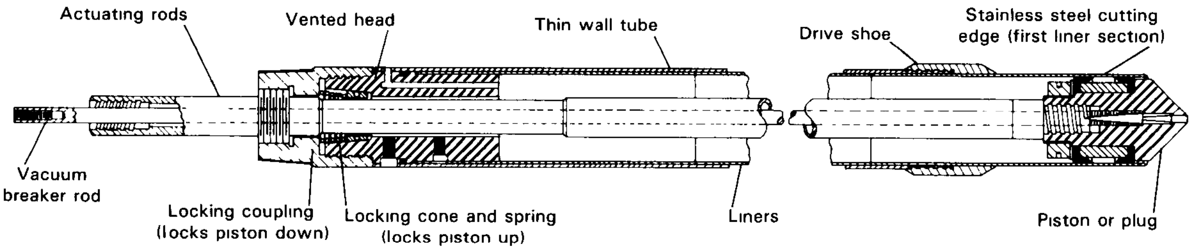


Figure 45.—Three and one-half-inch Lowe-Acker piston-plug sampler (Acker, 1974, figure 79, reprinted by permission from Acker Drill Co., Inc.).

plastic (polyethylene or nylon) are unsatisfactory because the laminae tend to separate, rigidity is low, and moisture transmission is relatively high.

The three principal sample characteristics that relate to geohydrologic tests are: (1) representativeness of the sample, (2) relative magnitude of effects caused by disturbance in the sample, and (3) accuracy of measurement.

Representativeness

The representativeness of a given sample is a function of variability in the sample in relation to the scale of variability in the formation from which the sample is taken. For example, a completely homogeneous, isotropic material requires only one sample, infinitely variable material requires an infinite number of samples. Statistical approaches are available for attacking this problem, but, because of its complexity, the problem is considered to be beyond the scope of this discussion. The two remaining considerations are discussed in the following paragraphs.

Compaction

Most coring operations result in some mechanical disturbance of the grain structure of the samples. Granular, noncohesive sediments usually tend to compact during sampling, as their grain structure collapses slightly from vibration of the drilling tool. Thick-wall samplers may increase the apparent volume of some sands as a result of displacement by the wall of the tube, but, regardless of whether the sand compacts or expands, grain structure is likely to be disturbed. Clays and fine silts are usually compressed by the pressures of sampling devices; changes in bulk volume of 15–20 percent are not uncommon.

Drive sampling usually causes greater compaction of samples than other methods of sampling, particularly in granular, noncohesive sediments. The amount of compaction may be directly related to the size of the core. Data suggest that the amount of compaction can probably be closely correlated to the number of hammer impacts and the total energy absorbed by the sample in the driving process. Although no quantitative data are available on this point, we suspecte that any drive sample requiring more than 20 or 25 blows per ft, using a 30-in. drop with a 140-lb hammer, will be significantly disturbed, probably throughout its entire volume. This observation may not apply to tough, cohesive materials, such as till or dry clay; but, in noncohesive materials, a relatively small amount of vibration may produce unacceptable samples.

Data collected from our own investigations, as well as from other sources, also show that the ratio of bit diameter to tube diameter is critical in obtaining undisturbed samples. Ratios of bit diameter to tube diameter ranging from 0.99 to 0.995 gave best results in drive samples. Wall thickness of the sample tube is critical; best results are obtained with wall thicknesses as small as 0.08 in. Wall thicknesses greater than 0.1 in. produce significantly greater compaction in both clays and sands.

Experience with drive samples has shown that the length of drive should never exceed 18 in. and, for best results, should not be more than about 12 in. It has been demonstrated that the upper 6 in. of sample is often significantly disturbed by an 18-in. drive. To minimize this problem, the USGS Water Resources Division uses sets of three 6-in. liners and one 18-in. sampler, and, in most instances, discards and reserves the upper 6-in. length for noncritical uses. This procedure also allows one to discard the upper part of any sample that has been contaminated by drilling fluids or filled by cave-in material.

The amount of compression that occurs during sampling of cohesive sediments is closely related to the diameter of the samples. Wall friction tends to drag the material down along the walls, and, as a consequence, a relatively large volume of material may be compressed and otherwise disturbed. In compressible clays and organic-rich sediments, a diameter of 2½ or 3 in. may be barely sufficient to minimize wall effects, whereas, for less compressible sediments, a 2-in. diameter may be adequate.

Expansion

Expansion of sediments as overburdened loads are removed cannot be eliminated by any means known at the present, and the effect is largely independent of sample size. Some recently tested clays and silts were estimated to have expanded by nearly 10 percent, with consequent increases in porosity and hydraulic conductivity. Apparent moisture contents were correspondingly low. We suggest, therefore, that if hydraulic conductivities, porosities, or moisture contents are desired from samples that tend to expand, the samples should be given a consolidation test to determine the relationship between porosity and applied load. The theory of consolidation allows a calculation of hydraulic conductivity from the consolidation curve, and, based on numerous experiments, hydraulic conductivities calculated in this way are apparently better related to in-situ conditions than are permeameter tests.

Wall Effects

The wall effects referred to are those resulting from the confinement of samples in smooth-wall tubes for permeameter measurements. Laboratory experiments have demonstrated that apparent hydraulic conductivities may be significantly affected by the higher velocities of flow that occur along the walls of permeameter tubes. The effects can be correlated with medium-particle diameters in the samples.

Practical means of coping with this effect in the laboratory do not exist; the best means of minimizing errors resulting from wall effects is to obtain samples of a size sufficient to make such errors insignificant. An adequate protection against wall effects in granular sediments is to use cores with diameters at least 25 times the diameter of the coarsest particle in the sample. For example, if the diameters of an appreciable portion of a sample are 2 mm, the core should be at least 50 mm in diameter (approximately 2 in.).

Accuracy of Measurements

Most laboratory tests, including those for hydraulic conductivity, are routinely accomplished with measurement precision that allows probable errors to be less than a few percent. Accuracy of the test result in relation to some true value is largely determined by characteristics of the sample. Measured porosities, for example, may easily differ by as much as 20 percent from in-situ values, with corresponding errors in calculated volumetric moisture contents. The effects of such changes on measured hydraulic conductivities are made complex by changes and shape factors; in general, no simple relationship exists between porosity and hydraulic conductivity in natural sediments. However, data from uniform granular media suggest that hydraulic conductivity is a logarithmic function of pore-size distribution; alterations in porosity are expected to cause relatively large differences in hydraulic conductivity. Similar effects are probably true for moisture tensions and specific yields, as well as some other parameters.

These problems are most clearly related to samples having too small diameters. In general, the length of the sample is not as critical a factor as the diameter is in causing erroneous and misleading test results. However, extremes in either case are not desirable. Six-in. samples are more than sufficient for routine hydrologic tests; shorter samples may be used for most purposes. Unless the representativeness of the sample is in question, little is gained by using samples longer than 6 in., while dangers of disturbance are greatly increased as length increases.

Contamination of Samples

A major problem associated with the rotary-drilling method for obtaining cores is sample contamination by drilling fluid. Unfortunately, the most serious problems of contamination occur in the permeable, granular materials, where drilling fluids are most essential to the drilling operation.

Drilling fluid may contaminate the sample by penetrating the undisturbed material beneath the hole as drilling progresses or by entering the sample liner with the sample. When drive sampling is done at the bottom of a hole drilled with fluid, the sampler penetrates a layer of drilling fluid before entering undisturbed material. Where such exposure to drilling fluids has occurred, it is often impossible to determine the exact depth of penetration of fluids into the sample; thus, cores may be useless for geohydrologic tests. These problems can be minimized if the suggestions on mud control explained previously are adhered to. If proper mud-control practices are not followed, then one of the dry-drilling methods, such as hollow-stem auger drilling and drive coring, should be used.

Disturbances Following Sampling

Many of the disturbances that impair the usefulness of samples occur during shipment or storage of the samples. Mechanical rearrangement of the grain structure by shock, vibration, or freezing are the most common of these disturbances. For example, a fine-grained core that appreciably dries in the liner may undergo essentially irreversible structural changes in the clay fraction, changes that destroy the reliability of measurements even when resaturated.

Some suggestions for preserving samples follow:

1. Sample liners should be fitted with tight plastic caps and sealed with plastic electrical tape immediately upon removal from the core barrel. For storage periods longer than a week or two and for samples in which moisture contents are extremely critical, the liner should be enclosed in plastic bags and coated with wax. Paraffin has a relatively high transmittance for water vapor; hence, it is not suitable for long-term protection. A number of tough, flexible waxes that do not transmit water are available from oil companies; one of these waxes should be used in preference to paraffin. An example of the type of wax to use for this purpose would be the ML-45 lemon wax available from Standard Oil Distributors.

During recent sampling operations to determine very small moisture contents in a thick, unsaturated zone, samples were weighed on-site on scales calibrated against laboratory scales and then reweighed in the laboratory to determine whether moisture loss or gain occurred. The precautions above were effective in detecting any change in moisture content, and the added caution of on-site weighing is likely unnecessary under most conditions.

2. Samples should be protected from extreme temperature changes that may place thermal stresses on moisture distribution. Samples should be protected from freezing, because freezing would result in mechanical stresses on the particle structure as well as redistribution of the moisture.

3. Samples should be protected from shock during shipment; they should be treated as fragile items.

4. On-site storage should be for minimum lengths of time. If sampling is done over an extended period, groups of samples should be shipped at short intervals to the laboratory where they can be stored in a constant-temperature, constant-humidity room. Samples that are thrown into the back of a vehicle and carried about during a summer field season are generally of little value for laboratory testing.

Disturbed Samples

Where economics or other considerations dictate, disturbed samples may be used for determinations of particle-size distribution, specific gravity, and lithologic or mineralogic analysis. In using disturbed materials, the following considerations should be kept in mind. (1) Material being returned to the surface by a power auger can rarely be relied upon to represent actual particle-size distribution in the sediments peneterated, especially when auger drilling below the water table. Loose, granular materials encountered in the hole will probably contribute excessively to the sample appearing at the surface; fine-grained materials may not be recovered. Segregation of particle sizes occurs rapidly as granular materials are vibrated, and, in most cases, coarser materials are continuously returned ahead of finer materials. Thus, in most instances, a sample returned to the surface will not represent a true integration of lithologic conditions through the entire depth of the hole, nor can it be considered representative of conditions at any given depth. (2) Drill cuttings from unconsolidated formations, using rotary or percussion methods, are also rarely found to be representative samples. Both the rapid settling of larger particles and the washing out of fines tend to distort the particle-size distribution of samples taken from drilling fluids. (3) Samples for use in repacked hydraulic-conductivity tests should contain the complete range of particle sizes of the in-situ material, particularly the smallest particles. Laboratory research on the problem of relating hydraulic conductivity to particle-size distribution has confirmed the hypothesis that hydraulic conductivity is most strongly correlated with particle sizes in the smallest 10 percent of the size range. Thus, if any appreciable amount of fine-grained material is lost during sampling, values of hydraulic conductivity may easily be in error by an order of magnitude or more. Repacked samples for hydraulic- conductivity determinations are of minimal value even if no better samples are available. However, if possible, such tests should be run only on relatively uniform granular material, containing less than 10 percent of materials finer than very fine sand. Materials having sorting coefficients greater than about 2 (containing more than about 10 percent of particles less than 0.125 mm) cannot be repacked to ensure a near reproduction of original bulk densities or the intergranular geometrics.

These facts have been documented in tests conducted at the Idaho National Engineering Laboratory, Idaho, in which auger-drilled samples were compared with undisturbed samples of the same materials. Results of the tests confirm conclusions of personnel of the USGS Water Resources Division research project during several years of sampling with power augers.

Comparison between Undisturbed and Disturbed Samples

The most carefully obtained samples have been shown to be subject to disturbances that lead to uncertainties in tests performed on them. Why, then, incur the greatly increased costs in time and money that undisturbed samples require? The answer to this question cannot be given in general terms because it depends on whether or not potential gains appear to outweigh increased costs in any situation. In answering this question, realize that drill cuttings or auger-drilled samples are inadequate for many purposes, whereas carefully obtained undisturbed or representative samples provide the only possible basis for quantitative conclusions.

Experience has shown that, when good-quality samples are obtained, a relatively small number of them may provide a basis for extrapolation of data over a wide area. A particularly good example is the use of undisturbed samples to calibrate borehole-geophysical data. With present knowledge, data obtained by borehole-geophysical methods on moisture content, clay content, and porosities cannot be reliably quantitative, unless the results are calibrated against the best possible undisturbed samples from the formation. Once this calibration has been made for a given formation or area, geophysical- logging methods may provide quantitative data over a wide area at relatively low cost. In a somewhat similar manner, drill cuttings or auger-drilled samples may be calibrated against undisturbed samples, and in many cases it may then be possible to use readily available and relatively inexpensive data from the disturbed samples to evaluate aquifer characteristics over a wide area.

To summarize this discussion on sampling:

1. Undisturbed samples are essential for accurate laboratory determinations of hydraulic conductivity, porosity, moisture content, consolidation of clays, and the examination of sediments in thin sections after injection by plastics.
2. Sample-tube liners of rigid metal or plastic are a prerequisite for optimum sample conditions and for best results from certain hydrologic tests.
3. Some commercially available samplers are effective in providing adequate sample recovery with minimum disturbance, if certain precautions are observed in their use. Drive samplers may be used with caution in granular, noncohesive media to avoid compaction of the material. Coring by rotary-drilling methods offers some advantages over drive sampling but introduces the possibility of contaminating the sample with drilling fluids. The design of certain rotary samplers minimizes the problem of contamination by allowing the cutting shoe to precede the rotary bit. Piston-drive samplers are excellent for recovery of soft or compressible sediments.
4. The size of cores is critical in determining the reliability of geohydrologic tests; cores of too great length or too small diameter may be equally undependable for testing.

5. Much of the disturbance of samples from the standpoint of use in laboratory tests occurs following sampling, during storage, or during shipping. Disturbances may include desiccation and resulting compaction or mechanical rearrangement of the granular structure by shock or freezing.

6. Disturbed auger-drilled samples or drill cuttings are unreliable for geohydrologic tests because of the loss of fines, segregation of sizes, and the possibility of contamination. Disturbed samples should be repacked for tests of hydraulic conductivity only when the sample contains the complete range of particle sizes of the in-situ material.

7. Undisturbed samples of good quality are difficult to obtain and expensive to collect. Their use is justified whenever reliable data can be obtained in no other way and when results from a relatively few undisturbed samples can provide a quantitative basis for alternative methods, such as borehole geophysics, that can be applied at relatively low cost over wide areas.

WELL-DEVELOPMENT TECHNIQUES

Any drilling method is going to create changes in the aquifer materials immediately adjacent to the borehole wall, changes that will require well development to remove the introduced fines, to loosen or redistribute compacted granular materials, and to remove some of the normal fines of the aquifer materials surrounding the borehole. Well efficiency can be increased if permeability of the formation can be increased for a considerable distance surrounding the borehole. Remove enough of the fines in the vicinity of the borehole wall to complete a natural, coarse-grained sand pack around the screen that bridges and prevents fine sands from entering the well so that excessive wear of pump parts will not occur in the normal production process. An idealized illustration of this is shown in "Ground Water and Wells" (Universal Oil Products, 1966). Even if it were not possible to increase the efficiency of the well by removal of an appreciable amount of the fines in the formation surrounding the borehole wall, the problems induced by drilling the well must be corrected to have an observation or production well that is responsive to the aquifer in which the well is completed.

The processes that caused the problems of decreasing the permeability of the aquifer must be reversed. These primary deleterious processes are filter cake, invasion of mud and other fines, and redistribution of compacted materials. There are available methods to accomplish all of this, but the problem must be understood before it can be solved. As mentioned, all well-drilling methods result in some damage to the formation materials penetrated, although variable conditions can exist that would change the order. The standard drilling methods that cause the most damage to the aquifer and result in greater need for development are: (1) mud rotary, particularly when proper drilling-mud control is not practiced; (2) auger drilling because of rind and plastering effect; (3) cable tool, due to compaction from driving casing; (4) reverse rotary, if drilling mud has to be added to make up water to slow or stop fluid loss (this method can result in difficulties equal to mud rotary); and (5) air-rotary drilling.

Following is a review of these drilling methods and resulting problems.

1. When a well is drilled by the mud-rotary method, build a mud cake to stop fluid loss and help support the hole wall. Prior to forming this mud cake through the filtrate process, considerable invasion of clay, silt, and fine sands can invade permeable zones. The depth of invasion can be considerable, depending on drilling-mud control, hydrostatic head of the drill fluid, and permeability of the aquifer material. Development effort and stress on the aquifer are going to be needed to develop a mud-rotary drilled hole.

2. An auger-drilled hole can cause nearly as much damage to the well as mud-rotary drilling because of the plastering effects of finer grained materials on the wall of the hole. Two exceptions to this, however, are when the hole collapses and a screen can be washed into the caved materials opposite the aquifer and or when a well point can be driven into an aquifer at the bottom of the hole.

3. Cable-tool drilling is a cleaner method than either of the two drilling methods described previously, but some small amount of invasion occurs from the up-and-down surging motion of the bit. The greatest hole damage by the cable-tool method occurs by compaction of the materials as a result of driving the casing through unconsolidated

formations. Common practice is to install a screen in the aquifer by the pull-back method when drilling with cable tool—that is, the hole is drilled and the casing is driven into the aquifer; the hole is bailed clean of cuttings; the screen is run to the bottom; and the casing is pulled or jacked back exposing the screen to the aquifer material. The aquifer material must be restored to its original porosity and permeability if a properly responding well is to result. However, methods for development of a cable-tool drilled hole are almost always easier to apply than those used for developing a hole drilled by the mud-rotary method.

4. Reverse-rotary drilling does not damage and contaminate the aquifer as greatly as many other drilling methods do and, therefore, is considered to be a clean drilling method. For that reason, many people feel that no development of reverse-rotary holes is needed. However, this is a misconception because, even under ideal conditions, a small amount of invasion of solids and filter cake forms from the partially reused drilling fluid that contains suspended sediments. The hydrostatic head of the fluid in the hole almost always exceeds that in the formation. Therefore, some of this suspended sediment will invade permeable zones and form thin filter caking. A simple method, such as over-pumping the well, may be successful in development of the well in this instance. However, there are times when drilling muds, possibly even with lost circulation additives, must be used to prevent too much or even total water loss. If this is the case, then the reverse-rotary drilled hole must be treated and development procedures used similar to those applied to mud-rotary drilled wells.

5. Air-rotary-drilled holes are probably the cleanest of all methods, particularly if no mud additives are needed in drilling the hole. However, this does not mean that no invasion of fines into fractures or highly permeable granular material occurs because the cuttings have to be forced out of the hole. Also, invasion occurs if the hydrostatic head in the hole is greater than the hydrostatic head in the formation. Various methods of well development are performed to reverse contamination caused by drilling. Most of the useful methods of well development are covered in available literature; therefore, we comment only briefly on those. The development problems and techniques inherent in the development of small-diameter observation wells are discussed in more detail. A method of well development using inflatable packers also is described, because this method is not treated in the other literature.

Backwashing

We use the example of backwashing first because some of the ways it is applied demonstrate the worst techniques available for well development. A good example of a poor development technique would be the case where a small-diameter observation well with well point is installed in a mud-rotary drilled hole, a hose is attached to the top of the well casing, and water is pumped through the screen until the drilling mud has been displaced from the hole. This is a necessary first step prior to development; however, it accomplishes nothing in the process of development because a negative hydrostatic head has not been applied to the inside of the well to remove the filter cake. Unfortunately, this is the only development step taken in the installation of many observations wells, and it is valueless. The backwashing method may be successful only in an auger-drilled hole where the aquifer material has collapsed and a well point has been pushed or washed into the collapsed material. In this case, backwashing can wash the screen clear and lift the material in a suspended slurry; by gradually slowing the backwash discharge to zero, the coarser materials will settle back around the screen first. The backwashing method referred to as rawhiding has some merit (Universal Oil Products, 1966, p. 306–307).

Air Surging

Air surging is the most used method for development of wells, particularly for holes drilled by the rotary method and in situations where air-line submergence is possible (about 50 percent) to pump the well by the air-lift method. Both Universal Oil Products (1966, p. 303–305) and (Anderson, 1967, p. 120–121) provide excellent data on submergence ratios, required air volumes, and equipment required for using the air-lift system. Universal Oil Products (1966) also explained the technique of development by air. We believe the air-lift technique, when it can be used, is a very good method of development; however, any large amount of air introduced into the aquifer is harmful, and the back-blow process can, and usually does, force some air into the aquifer; so this process must be used with caution so as not to cause air locking of the aquifer. Entrapped air in the granular pore spaces can be as difficult to remove from the aquifer as fine materials are; too much air introduced into the aquifer can, at least temporarily, completely plug it.

Mechanical Surging

Mechanical surging or surge-block development of a wall is a method that applies a minimum of stress to the aquifer but is often adequate to develop wells that will produce a minimum of invasion or disturbance of the aquifer. This technique is commonly used as the only method for development of cable-tool drilled holes because of the easy up-and-down surging method obtainable through the spudding arm. The method also can be used on a rotary-type rig, but it requires considerable manipulation of the sandline winch by the operator, and it is usually not very successful in rotary-drilled holes where heavy filter caking and deep mud invasion have occurred. The method is well described by Universal Oil Products (1966, p. 299–303).

Overpumping

The overpumping method is simple and often is the only method used in development of reverse-rotary drilled holes. However, if the development pump does not have a much greater capacity than the intended production pump, enough fine sand may not be removed from the aquifer to properly develop it, resulting in later sand pumping and damage to the production pump. The reader is again referred to Universal Oil Products (1966, p. 305–306) for more details of this development method.

High-Velocity Jetting

High-velocity jetting is the best method available for destroying the integrity of the filter cake, particularly if the screen is close to the hole wall, and to stir up the material surrounding the screen. High-velocity jetting is also an excellent method of development in wells that can be completed in open hole without casing. In rock or consolidated lithologies, the only materials that have to be dislodged and removed from the well are the filter-cake membrane or rind left on the hole wall as a result of drilling and a possible small invasion of clay. The high-velocity jet will do an excellent job of flushing this filter cake off the hole wall. After the filter cake is disintegrated, it will remain in fluid suspension for a short period of time and can be pumped or bailed from the well. The method is described by Universal Oil Products (1966, p. 307–309); however, we emphasize some points made and add some suggestions that will improve the method:

1. It is suggested, where possible, to pump the well lightly at the same time that the high-velocity jet is working. This is not always practicable, but should be done where the size of the well, the available equipment, and the position of the static-water level in the well permit. Pumping of the well (preferably by air) should be done whenever possible, and not "lightly." The greatest stress that can be applied to the aquifer while using the high-velocity jetting technique will bring more fine materials into the well, doing a better job of development, and, at the same time, the heavy pumping will remove most of the fine materials from the hole.

2. The jetting tool (Universal Oil Products, 1966, fig. 288) must fit as closely as possible in the screen section being jetted. Do not use a 6-in.-diameter jetting tool in an 8- or 10-in. screen, because if the jetting tool is centered in the hole, the 1 or 2 in. of water surrounding the tool will greatly slow the velocity rate of the jet. Because most drill holes are not vertical, the tool probably will be dragging on one side of the hole, resulting in good energy application to one side of the screen and poor energy application to the other side, from the velocity lost through 2–4 in. of water. The result would be partial development of the formation, and this result only can be overcome by fitting the tool to the screen diameter.

3. When a two- or four-nozzle high-velocity jetting tool is used and is slowly turned and raised in the screen in an attempt to cover all areas of the screen, it is unlikely that the entire screen area has been covered. We prefer to use a well-development jetting tool (fig. 46) of a design that provides better coverage of the screen area. Four horizontal slots are cut through the jetting tool to a length of ½in.

The wedge shape of the water jet provides about one-half coverage of a 6-in. screen, resulting in a minimum turning of the pipe. However, this tool requires more pump capacity to operate it than the one illustrated by Universal Oil Products (1966). The standard jetting tool with four 3/16-in. nozzles requires about 48 gal/min for velocities of 150 ft/min, while the slotted jetting tool (shown in fig. 46) requires about 115 gal/min to obtain the same velocity.

Chemical Treatment

Many polyphosphates (deflocculents), such as sodium hexametaphosphate, sodium pyrophosphate, and sodium tripolyphosphate can be added to the water in the well at a rate of about 5 lb of additive to 100 gal of water to help break down the gel properties of the drilling mud and disperse the clay particles by separating them from the sand particles in the aquifer. These additives should be pumped into the well and agitated, particularly if the annular area of a gravel pack is filled by some surging or agitation with a bailer. Some combination polyphosphate-light acid products are on the market, such as Coty Chemical Corporation, Dry Acid, and Johnson, Nu Well, that have helped remove clays and drill muds from wells; they are safe to transport and handle. Coty Chemical Corporation recommends "the use of ½ to ¾ pounds of 'Dry Acid' per gallon of water in the hole." Dry Acid should remain in the hole for at least 24 hours and should be agitated with a bailer every few hours. After the solution has been in the hole the prescribed amount of time, it should then be removed from the hole and normal development methods used to complete the well.

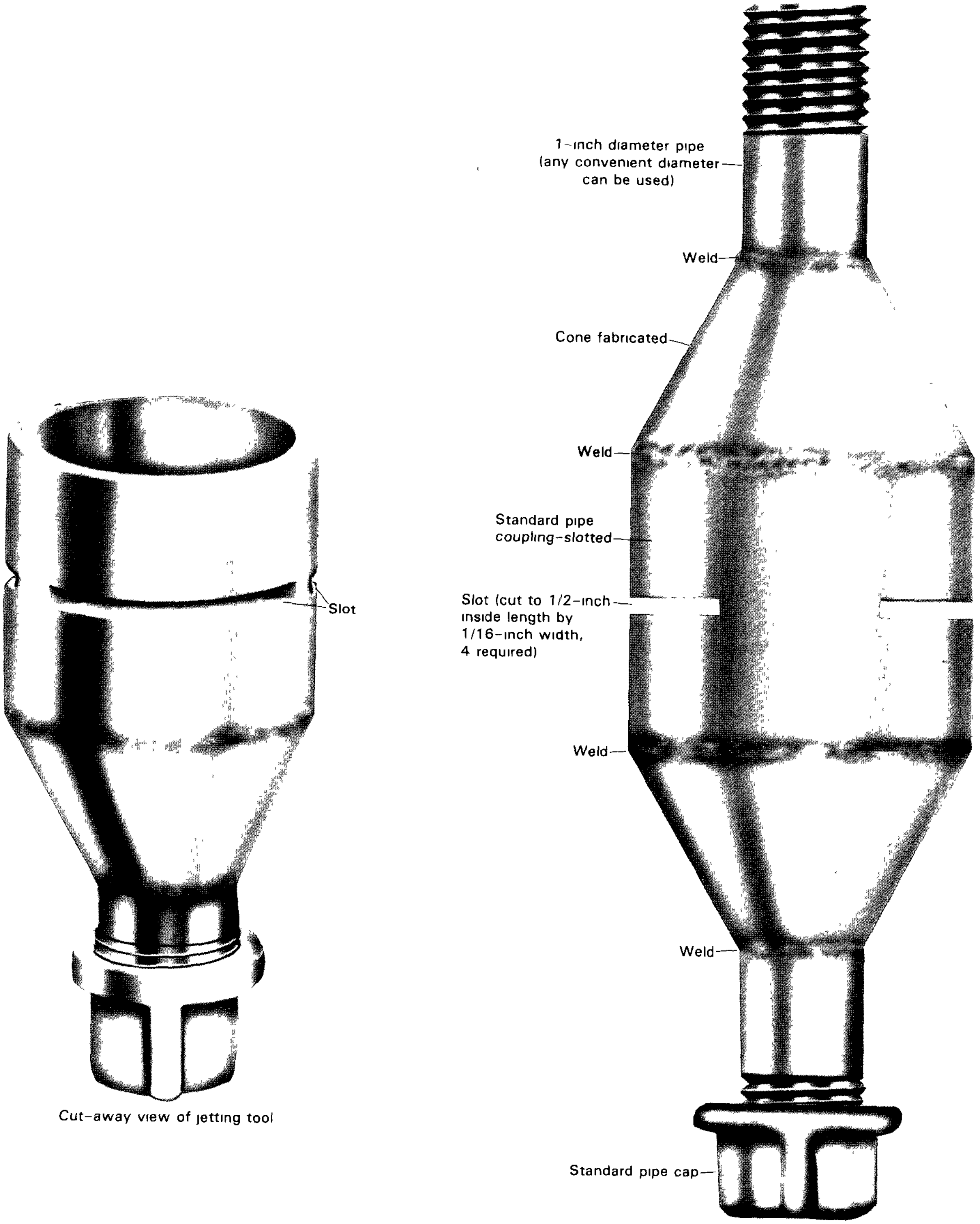
"Nu Well" by Johnson is a pelletized chemical treatment primarily used for removing deposits of calcium and magnesium from encrusted water-well screens. The amount of Nu Well to be placed in the well for satisfactory results is about 30 percent or more of the weight of water contained in the well screen. Allow about 2–4 hr for the pellets to dissolve; then surge the solution to spread the solution's coverage in the well and hasten breakup of the encrusting material. After agitating, best results are obtained when the solution is allowed to remain in the well overnight. The Nu Well contains a pH indicator that changes from a dark purple or red color to an orange or yellow color after reacting with the incrustant. When the orange or yellow color is evident in the well fluid, it denotes the change from a strong acid solution to a weak solution. When this occurs, agitate and pump or bail the solution from the well and dispose of the used Nu Well in a safe place. After removal, normal development methods can be resumed to complete the well.

Development of Selected Well-Screen Intervals

Even when all available well-development methods previously described are used according to recommended procedures wells are not entirely developed to their greatest potential. This is particularly true in wells screened in thick, high-yielding aquifers where enough stress cannot be applied to the aquifer to pull the fines in. If spinner- or tracejector-flow tests, conducted while the well is pumping indicate that certain areas of the aquifer are not producing, these zones can be developed by the straddle packer and swabbing technique. However, this method of well development is complex and expensive. This method is often used by Water Resources Division in hydrologic testing of open holes, but it is almost never used as a development procedure in screened wells or perforated-casing holes.

As an example, assume development of a preselected 20-ft interval of an 8-in.-diameter screen:

1. Two air-inflatable packers are coupled together with a 20-ft section of slotted screen straddled between them (fig. 47). The slotted screen should have a diameter slightly larger than the diameter of the deflated packers, and the slot size of the screen should be larger than that of the aquifer screen so that all fine materials removed from the aquifer can readily pass through the packer screen.
2. Nylaflow tubing (¼-in. I.D.) is coupled to the inflation fittings of each of the packers. The straddle tool is then run into the hole on pieces of 4-in. flush-joint casing, and the Nylaflow tubing is taped to the casing at about every 20 ft interval.
3. When the desired depth for well development is reached, the flush-joint casing is set on the well casing by means of a tubing clamp, and the upper end of the packer pipe is affixed with a tee fitting for later discharge of water when swabbing. The packers are then ready to be inflated. To determine the inflation pressure, compute the pressure needed to overcome the static water-level head above the



Cut-away view of jetting tool

Figure 46.—Fabricated high-velocity well-development jetting tool.

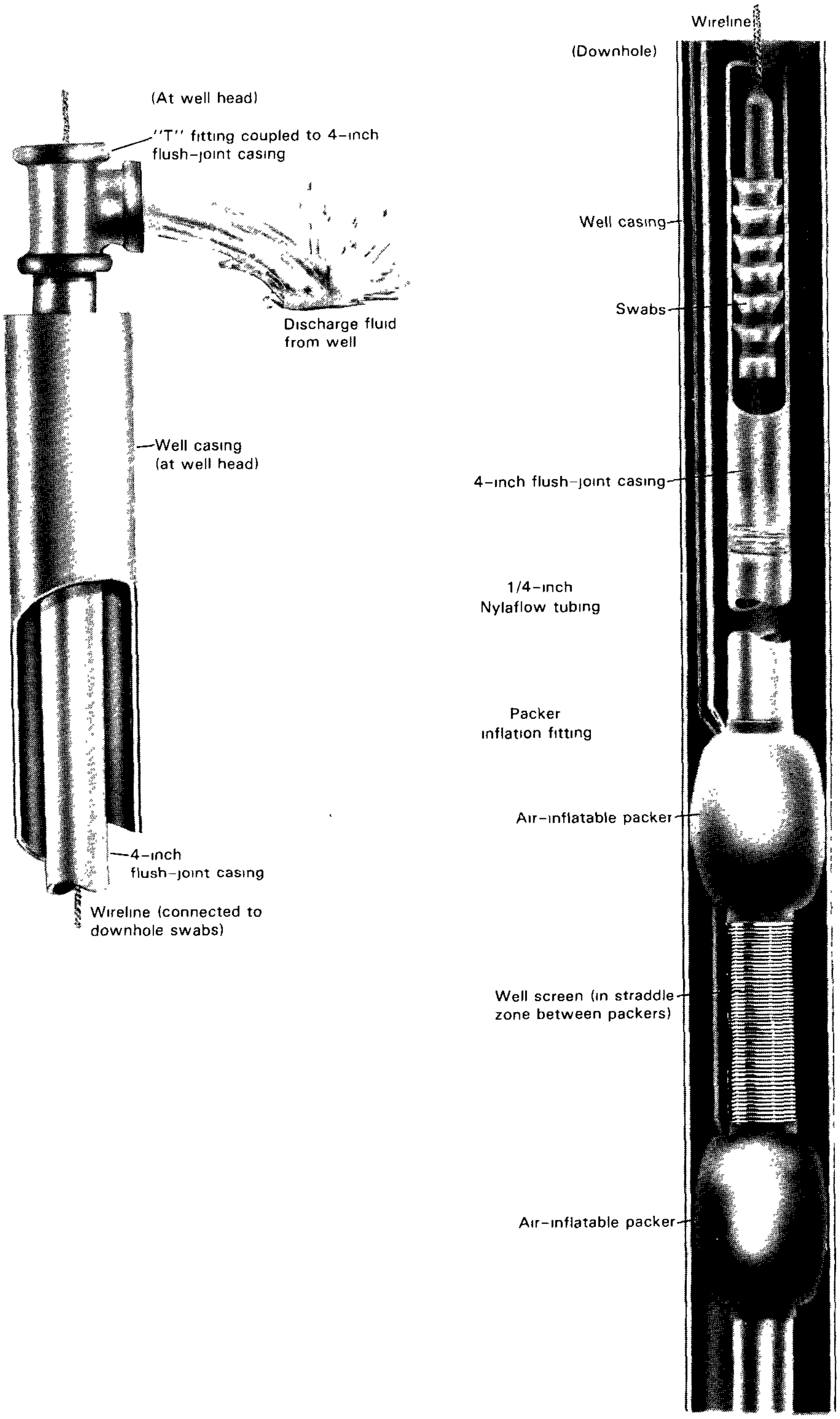


Figure 47.—Straddle packer and well-swabbing equipment used for well development.

packers; to this amount add 50 lb/in.^{2} to inflate the packers to the screen; and apply about 75–100 lb/in.^{2} more pressure against the screen. For example, if the packers are to be set 300 ft below the static-water level use 130 lb/in.^{2} to overcome the water-level head plus 50 lb/in.^{2} to inflate the packers to the screen plus 75 lb/in.^{2} more pressure against the screen, or a total of 255 lb/in.^{2} inflation pressure.

4. After setting the straddled packers in the hole and inflating them, the swab (we prefer the Mission cup type) is run in on a sandline to a depth of 50–75 ft below the water level. Initially, the swab is raised out of the hole at a rate of about 100 ft/min so that the swab cups open and trap all the water above the swab. The swab is brought all the way to the surface, discharging the water out the tee. As soon as the swab has dumped the load of water, it is immediately lowered back down the hole and the depth at which it enters the water (easily detected by slacking the line or sound) is noted. If the water level has not recovered to the initial static-water level in this short time, swabbing is continued using about 50-ft intervals and the recovery rate is observed. If the recovery rate does not increase, the swab should be lowered about 100 ft below the water level and pulled at a faster rate (200 ft/min). This procedure will produce a discharge rate of about 125 gal/min and will likely impart an instantaneous head difference of about 100 ft (plus the vacuum applied from the swab) to the borehole wall thereby breaking down any filter cake and pulling the fine materials into the swab casing. Note: If discharge of sand at the fluid effluent pipe tee indicates that a considerable amount of sand has entered the swabbing casing, halt swabbing temporarily and run in a wash pipe or small bailer to clean out the sand, since large amounts of sand above the swab cups can sandlock them in the casing. After removing the sand, additional swabbing of the well should be performed.

This method of well development is very effective and can be conducted at any desired intervals. Note: When working at considerable depths below static-water level, never attempt to lower the swabs too deep below the water level and pull an instantaneous 500- to 600-ft column of water. This practice can damage the packers and may even damage the screen. After zone development has been completed, the packers are deflated and returned to the surface or reset at a different depth and another zone developed by the same process.

Development of Gravel-Packed Wells

A common erroneous assumption among drillers is that little or no development is needed in wells constructed by the gravel-packed method. Actually, if the well was drilled by the mud-rotary method and the screened zone is underreamed to a larger diameter to accommodate a larger gravel envelope (which is a common procedure for gravel-packed constructed wells), then development of the aquifer through the gravel packing will be much more difficult than development of a natural-packed well. Gravel packing of wells generates difficulties in aquifer development, and the method should be used only when proper screens cannot be selected to prevent sand pumping (Universal Oil Products, 1966, p. 310–311).

An example of the difficulty encountered in the development of a gravel-packed well follows: Two wells were constructed in the same aquifer, consisting of relatively fine, slightly cemented sand. One well was completed with 105 ft of 8-in.-diameter stainless-steel slotted screen installed in a close-tolerance, mud-rotary drilled hole. The other well was completed using 125 ft of a shutter-type screen installed in an underreamed 36-in. hole and was gravel packed. After five days of development, using the high-velocity jetting method to remove the drilling mud and other fine materials from the well, the specific capacity (gallons per minute per foot of drawdown) of the natural-pack well was 17.4 gal/min/ft, a good specific capacity for fine sand. On the other hand, after 30 days of development of the gravel-packed well by the surging and backwashing method, the specific capacity only reached 1.3 gal/min/ft of drawdown, a very poor specific capacity for fine sand. This low specific capacity probably was a result of having underreamed to a diameter larger than desirable.

An energy means, such as surging, high-velocity jetting, and pumping, must be present in the borehole to create a positive head in the formation and a negative head in the well to break down the filter cake on the wall of the hole and remove fine materials, to develop an aquifer to its full potential. The following example indicates the impossibility of accomplishing this in a gravel-packed well. High-velocity jetting, which was very successful for developing the natural-pack well, was valueless in the development of the gravel pack, because the thick gravel envelope absorbed all the energy imparted by the high-velocity jetting tool; and all that was accomplished in the well was the creation of a greater positive-hydrostatic head against the filter cake. Mechanical surging and backwashing will only result in water moving up and down in the permeable gravel pack section of the hole, resulting in little or no negative head energy being imparted to the filter cake. Since the filter cake is a rubbery membrane having little or no permeability and very little supportive strength, except when the hydrostatic head is greater in the hole than in the formation, it can only be destroyed if the hydrostatic heads are reversed. However, the gravel pack gives internal support also, and it cannot be removed by stressing the aquifer. If gravel packing has to be done in the well, the gravel envelope should be kept as thin as possible so that the various development techniques employed have a chance of breaking down the filter cake and developing the formation.

DEVELOPMENT OF SMALL-DIAMETER WELLS

Development principles of all wells are the same. However, small-diameter observation wells, because of the small diameter and the fact that many of these wells penetrate the aquifer to a shallow depth, pose particular problems that require different development techniques than those used for development of large-diameter wells. As part of an observation-well maintenance program, the wells should be slug tested or pumped periodically to confirm that they are open and responsive to the aquifer.

An observation well should be developed immediately after its installation. Too often, as an expediency when a large number of observation wells are installed on a particular project, the decision is made to delay the development of the wells until a later time. This always results in more development effort, and, in most cases, later development is impossible to accomplish.

Air Development

In the first example, assume a 2-in.-diameter well with a 2- or 3-ft well point or screen at the bottom is to be developed, and, upon sounding the well, no appreciable amount of fine sediments has been found in the bottom of it. Also, enough water was in the well pipe to allow the proper submergence of an air line for development of the well by the air-lifting method. A fabricated air nozzle (as shown in fig. 48) is connected to the bottom of ½-in. pipe and then lowered into the well until the proper submergence depth is reached. The upper end of the pipe or tubing is connected to a compressor, and enough air is slowly provided to pump water out of the pipe. If the water level is pumped down to a level where only air is blowing out of the pipe, lower the air line further into the well pipe until the well again produces water. Lowering the air line can be continued, but it should not be lowered into the well screen, which might allow air to be introduced into the aquifer. If the air pumping has created enough static-head difference to begin well development by causing fine sediments to enter through the well screen, it will be evident from the amount of turbidity in the discharge water. Continue to pump until the water clears. If development is successful, an appreciable increase in discharge will be noticeable. Occasionally, use of this method of development can cause a considerable amount of fine sand to enter the well; if the fine sand cannot be lifted out in the ascending column of water, it must be removed by other means, or it will resettle in the well and again plug the screen. If the above occurs, the air jet should not be lowered into the screen to blow it out. Instead, the air line is removed from the hole; the ¼-in. pipe plug is unscrewed from the jetting tool and replaced with a ¼- by 2-in. nipple. The ½-in. pipe is then lowered back into the hole to a point just above the fill in; it is connected to the water pump; and the sand is jetted out of the well. Some of the water will come out of the small jets in the jetting tool, but the largest volume of water will pass through the ¼-in. pipe, permitting flushing out of the fine materials. After the fines have been flushed out of the well pipe, the screen should be cleaned by jetting while the tool is still at the bottom of the well. To accomplish this, the bottom of the jetting tool must first be sealed again by dropping a 7⁄16-in. or ⅜-in. steel ball bearing down the ½-in. jetting pipe and letting it seat on the ¼-in. pipe nipple. Or a 3⁄16 by 1- or 2-in. bolt can be used instead of a ball bearing; the bolt is dropped down the pipe, thread end first, and the head of the bolt will seat on the ¼-in. pipe. The jetting tool can be used nowas a high-velocity jetting tool to clean the

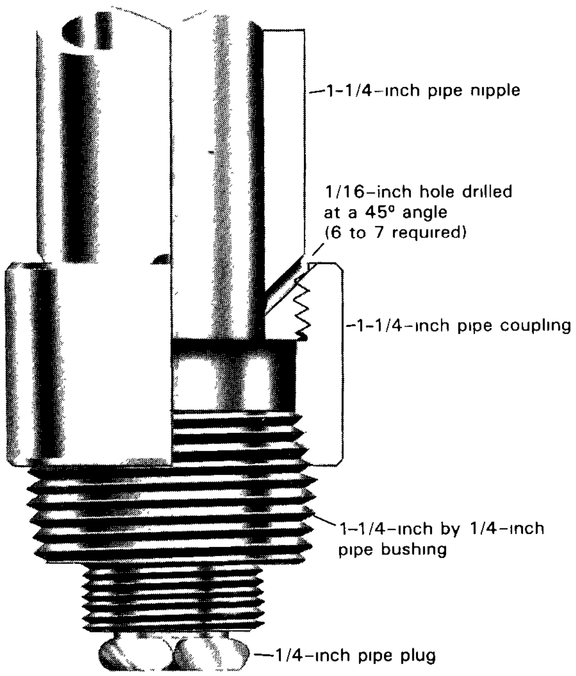


Figure 48.—Fabricated air nozzle for development of small-diameter wells by the air-lifting method.

screen. After jetting, the ½-in. line is pulled back up the hole some distance, the compressor reconnected, and additional air pumping performed as necessary to complete the well-development process.

Sometimes, observation wells penetrate the aquifer to such a shallow depth that the method of air pumping previously described cannot effectively be accomplished. However, there is an air-development method that may provide adequate results for such wells. For example, assume an observation well has a static-water level of 50 ft, and only 10 ft of water in the well is above the screen. This well cannot be pumped in the manner previously described; however, air can be used to blow water out of the well by the following method. The air line with the jetting tool attached (with the ¼-in. pipe plug in place in the jetting tool) is lowered into the well to a point about 5 ft below the surface of the water, and the compressor line is attached to the air line. A rapid, large, upward surge of air will blow the water out of the well. After the water has been blown out of the well, the process is repeated after waiting several minutes. The amount of the second discharge of water should be observed and compared to the first amount discharged from the well. If little or no water discharges on the second surge, the air line is lowered another few feet in the well but not so far down that the air jets are discharging inside the screen. This procedure including the resting and resurging is repeated. If dirty water starts to be discharged from the well and as much water discharge is observed in the second surge as occurred in the first surge, the well is developing, but do not continue to surge air at this same depth. As the well starts to make water, the air pressure must be increased to lift the heavier water column, and this may result in back pressuring of air through the screen and into the aquifer. The air line is raised in the well and the blowing-out procedure is continued.

If this method does not develop the well, because of the very low stress that can be applied to the aquifer, the high-velocity jetting method should be used to clean the screen and one of the suggested polyphosphates or low-acid combinations added to the well. If the screen or formation is so plugged that it will not take the additives, they may be forced out into the formation by filling the well pipe with water or even connecting a pump to the pipe and backwashing them into the formation.

High-Velocity Jetting

Some observation wells, because of too large a screen-size selection, may contain a considerable amount of materials that entered the pipe through the screen when the well was installed. If the well was not developed at the time that it was installed, the materials gradually settle out and create a completely sealed and nonresponsive observation well. To develop a well where this has occurred, remove the sediments from the inside of the pipe using the jetting-washout method. After the sediments have been washed out of the well, the ball bearing or the bolt is dropped into the fabricated air nozzle and high-velocity jetting is performed through the screen, for cleaning of the screen and agitation of the materials around the screen. This process may provide adequate development; if it does not, then one or more of the following techniques can be used.

Swabbing

Swabbing of small-diameter wells as a development method is probably the most positive development technique available, particularly if it is performed at the time of installation and if the well penetrates at least 30 ft into the aquifer. Small-diameter swabs of the Mission type can be obtained in sizes of 1¼ in., 1½ in., and 2 in.; these will accommodate the range of most small-diameter observation wells. The swabbing technique for small-diameter wells is the same as that described beginning on page 88, except packers are not used. Certain precautions must be used in swabbing development of small-diameter wells:

1. Swab cups are manufactured to operate in flush-joint tubing. Although they will operate in standard coupled steel or plastic pipe, the user must ensure against two things that will either prevent them from being lowered through the pipe or will tear the cups up when the swab is pulled: (1) if a steel pipe is used, each end of the pipe must be reamed to remove any sharp cutting edges, (2) if plastic pipe of the cement-joint type is used, cement should be applied sparingly at the coupling so that excess cement does not form a ring or blockage inside the pipe.

2. If plastic pipe (and particularly plastic screens) are used in construction of the observation well, pulling too much water out with the swabs at one time may cause the screen to implode. This is particularly important when the well begins to develop, because water may not be entering the screen fast enough to equalize the head. Swabbing should begin by pulling no more than a 50-ft head. Then, if the well increases in yield and hydrostatic-head equalization is not a problem, the swabbing head can be increased to apply more stress on the aquifer.

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GLOSSARY

(Commonly used drilling and sampling terms)

Annulus	The annulus or annular space is the space between the outside diameter of the drill rods, drill pipe, or casing and the wall of the borehole.
Box	Female end of threaded drill-tool joint; see pin.
Casing	A pipe used to case a drill hole; special seamless tubing in which drill rods rotate; used to hold back overburden or to line cavernous drill holes.
Core	The cylinder of hard rock or unconsolidated material produced by the hollow, coring-type bit.
Dead-sticking	Process of moving a string of drilling tools up or down in a borehole without rotating them.
Derrick	The mast on a drilling rig used for supporting the tackle for drilling, hoisting, and lowering the drilling tools.
Drawworks	A power-driven winch or system of winches, usually equipped with clutch and brake (might also be hydraulically controlled system) for raising or lowering a drilling string.
Drill bit	The steel tool attached to the bottom end of the drill pipe which performs the actual drilling. Made in a variety of sizes, types, and shapes depending upon the type of lithology to be drilled, the method of drilling, and the depth and size of the hole.
Drill collar	A heavy steel tool that is attached at the lower end of a string of drill pipe and just above the bit to provide weight and stability to the drill tools for rotary drilling or coring.
Drill jars	A tool composed of two connected links having vertical play between them. Used to apply a sudden upward impact or shock to a string of drill tools stuck in the hole.
Drill pipe	See drill rod.
Drill rod	Special pipe, hollow flush-jointed or coupled rods joined and threaded at each end, used to transmit rotation from the rig rotating mechanism (rotary table); thrust or weight to the bit; conveys drilling fluid or air to remove cuttings from the hole and cool and lubricate the bit.
Drill stem	A steel tool that is attached below the drill jars in a string of drilling tools to provide weight to the tool string.
Fish	Debris in a borehole, such as broken bits, drill rod, core barrels, and tools which might have broken off or fallen into the hole.
Fishing	The attempt to recover debris from the borehole.
Fishing tools	Special tools (overshot, spear, junk basket, magnet) used to recover debris from a hole.
Fluid	Liquid or gas medium used for clearing cuttings from the borehole being drilled; stabilizes borehole wall; cools and lubricates bit and drill tools.
Flush-coupled casing	Seamless tubing having a box end and a pin end instead of using a coupling. Has the same outside diameter throughout. Flush-coupled casing is thinner walled than flush-joint casing.
Flush-joint casing	Seamless tubing having a box end and a pin end instead of using a coupling. Has the same inside diameter throughout. A special type of flush-joint casing is used for wireline coring.
Grab samples	Random lithologic samples taken as the borehole is being drilled or auger drilled. The samples are disturbed and usually contain a mixture of the materials being penetrated by the bit and transported to the surface in the drilling fluid or transported up the auger flights in an auger-drilled hole.
High-yield bentonite	A bentonite that will give a specific viscosity to the largest volume of water. The yield test relates the solid content to the viscosity of a clay-water mixture.
Hole conditioning	The process of circulating a drilling fluid in a borehole to remove drill cuttings, stabilize the borehole wall with a filter cake (rind), and prepare the hole for geophysical logging. Conditioning is usually performed after drilling or coring has been completed in the borehole.
Kelly	A formed or machined section of hollow drill steel which is connected directly to the swivel at the top and the drill rod below. Flutes, flats, or splines of the kelly engage the rotary table to transmit rotation to the kelly which is, in turn, transmitted to the drill rods and bit.
Overshot assembly	Wire-line-core barrel inner-barrel retrieval assembly. Lowered through the wire-line-drill rods on a wire line by means of a wire-line winch.
Packer	An inflatable cylinder of reinforced rubber and metal used to seal a well or borehole for hydraulic testing, grouting, or well-development purposes.
Pin	Male end of threaded drill-tool joint; see box.
Rope socket	A tool by which a connection is made between the drilling line and the drill stem used on a cable-tool drilling rig.
Shale shaker	A screened, vibratory drilling-mud cleaning device used to separate drilled cuttings out of the uphole flow of cuttings-laden drilling mud before the mud is recirculated back downhole.
Spot	To selectively place a quantity of drilling fluid at a particular depth in a borehole to control caving or fluid entry in that portion of the borehole, usually to facilitate lithologic sampling of that zone.
Spudding in	The starting of a hole.

Sub	A substitute or adaptor used to connect from one size or type of threaded drill rod or tool connection to another.
Swivel	A connection from a stationary hose into a rotating member, such as a kelly or drill rod, to allow passage of a drilling fluid or air and the free rotation of the rods.
Tremie (pipe)	A small-diameter pipe with a funnel like top through which grout is poured into a borehole.
Wire-line-core barrel	A core barrel in which the inner-barrel assembly and contained core may be retrieved to the surface by means of a wire-line with overshot assembly without removing the drill rods from the borehole.

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