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U.S. DEPARTMENT OF THE INTERIOR
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

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Book 2

COLLECTION OF ENVIRONMENTAL DATA

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

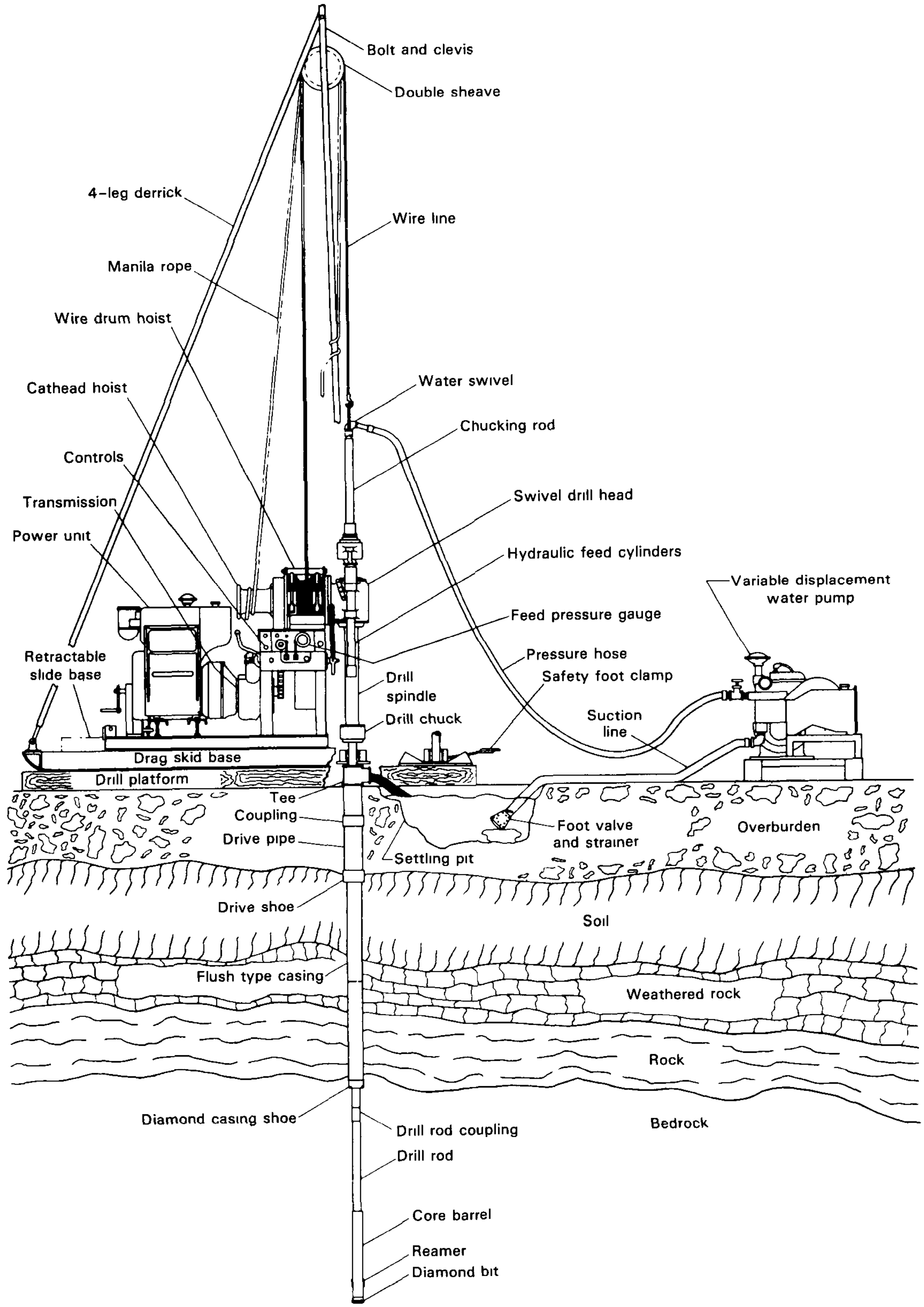


Figure 10.—Typical diamond-drilling rig for exploration (Acker, 1974, reprinted by permission from Acker Drill Co., Inc.).

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 IN.	OD MM	ID IN.	ID MM	THREADS PER IN.	WGT LBS/FT.	WGT KG/M	COUPLING-ID IN.	COUPLING-ID 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 IN.	OD MM	ID IN.	ID MM	THREADS PER IN.	WGT. LBS/FT.	WGT. KG/M	COUPLING-ID IN.	COUPLING-ID 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 IN.	OD MM	ID IN.	ID MM	THREADS PER IN.	WGT. LBS/FT.	WGT. 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 IN.	CORE DIAMETER IN.	"M" DESIGN SIZE	OD IN.	CORE DIAMETER IN.	"T" DESIGN SIZE	OD IN.	CORE DIAMETER 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 IN.	CORE DIAMETER 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 IN	CORE DIAM IN	SET DIMENSIONS (INCHES ± .005) OD	SET DIMENSIONS (INCHES ± .005) 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)

SIZE	CASING BITS OD	CASING BITS ID	CASING SHOE BITS OD	CASING SHOE BITS 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 OD	DRILL RODS ID	OUTER TUBE OD	OUTER TUBE ID	INNER TUBE		CORE BARRELS HOLE DIAM	CORE BARRELS CORE 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.).

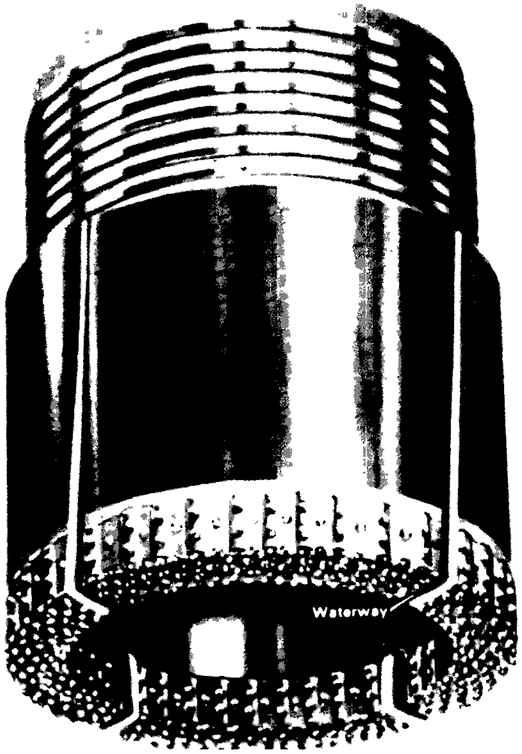


Figure 12.—Face-discharge diamond-core bit.

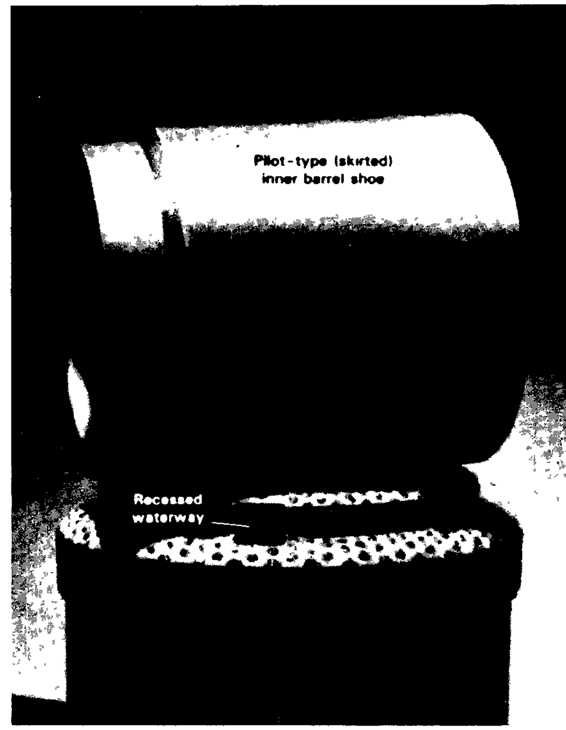


Figure 13.—Recessed bottom-discharge-type diamond-coring bit and pilot inner-barrel shoe.

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

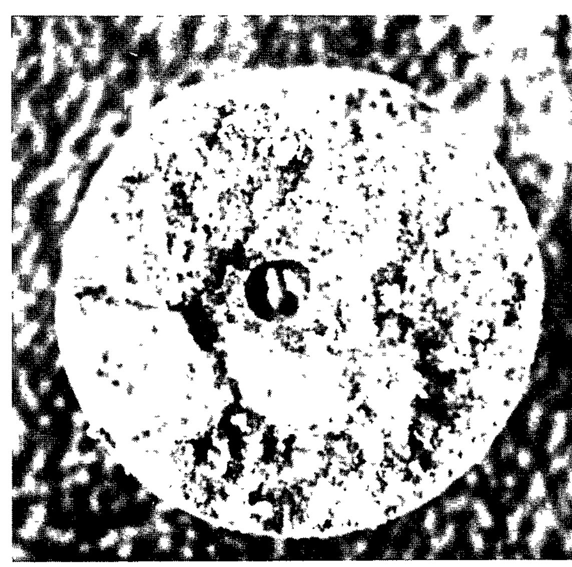


Figure 14.—Hydraulic-rotary core of unconsolidated, fine-grained Ogallala sand.

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

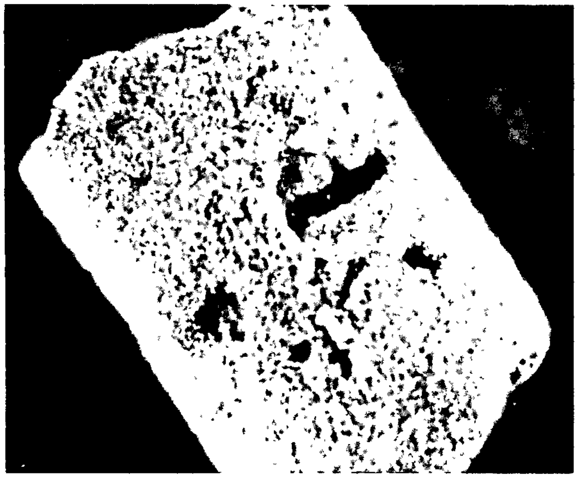


Figure 15.—Hydraulic-rotary core of loosely consolidated Ogallala sand with solution openings.

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

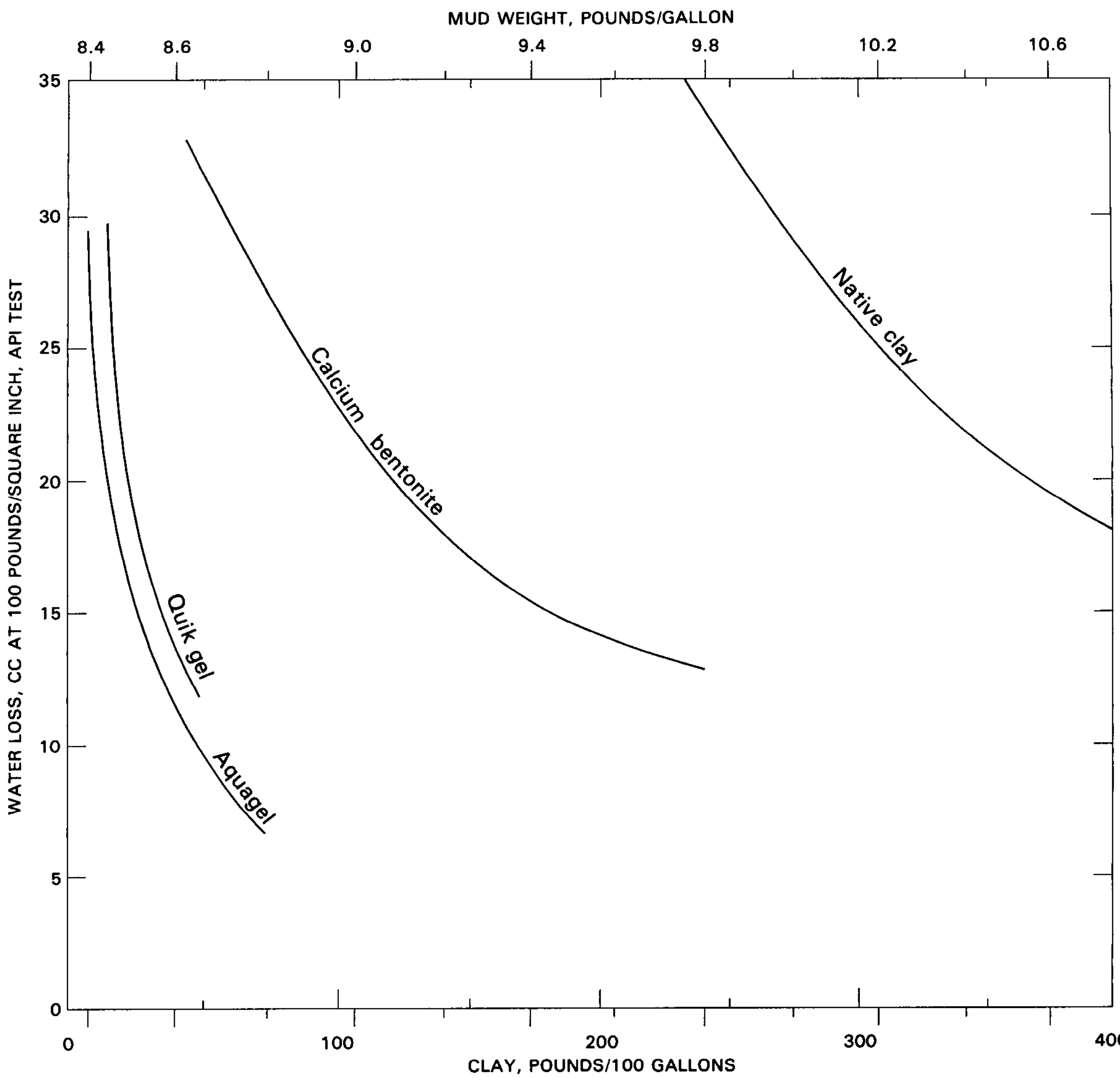


Figure 17.—Mud weight versus water loss.

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.

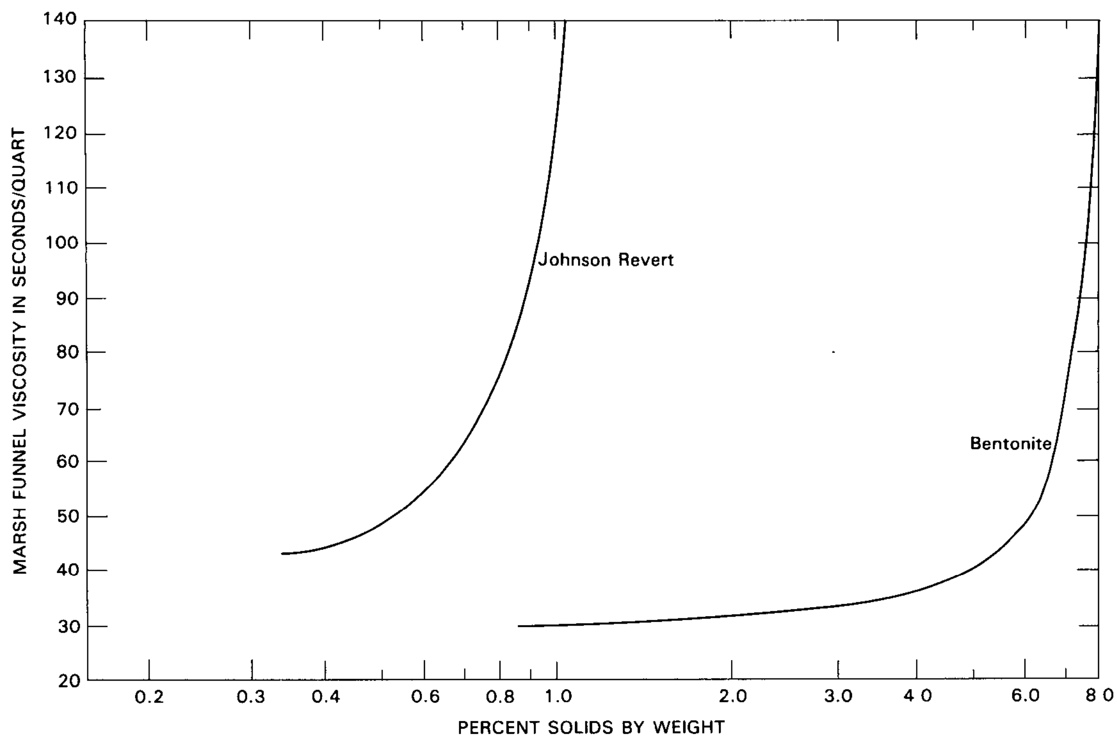


Figure 18.—Comparison between Marsh-funnel viscosity and percent solids, by weight for Revert and bentonite (Universal, 1966, reprinted by permission from Johnson Division, Universal Oil Prodicts, Inc.).

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

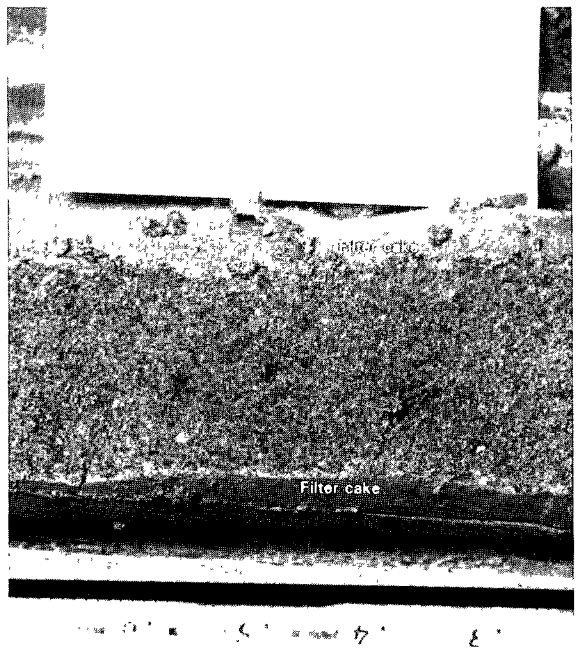


Figure 19.—Rotary core of an unconsolidated medium sand showing filter cake.

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

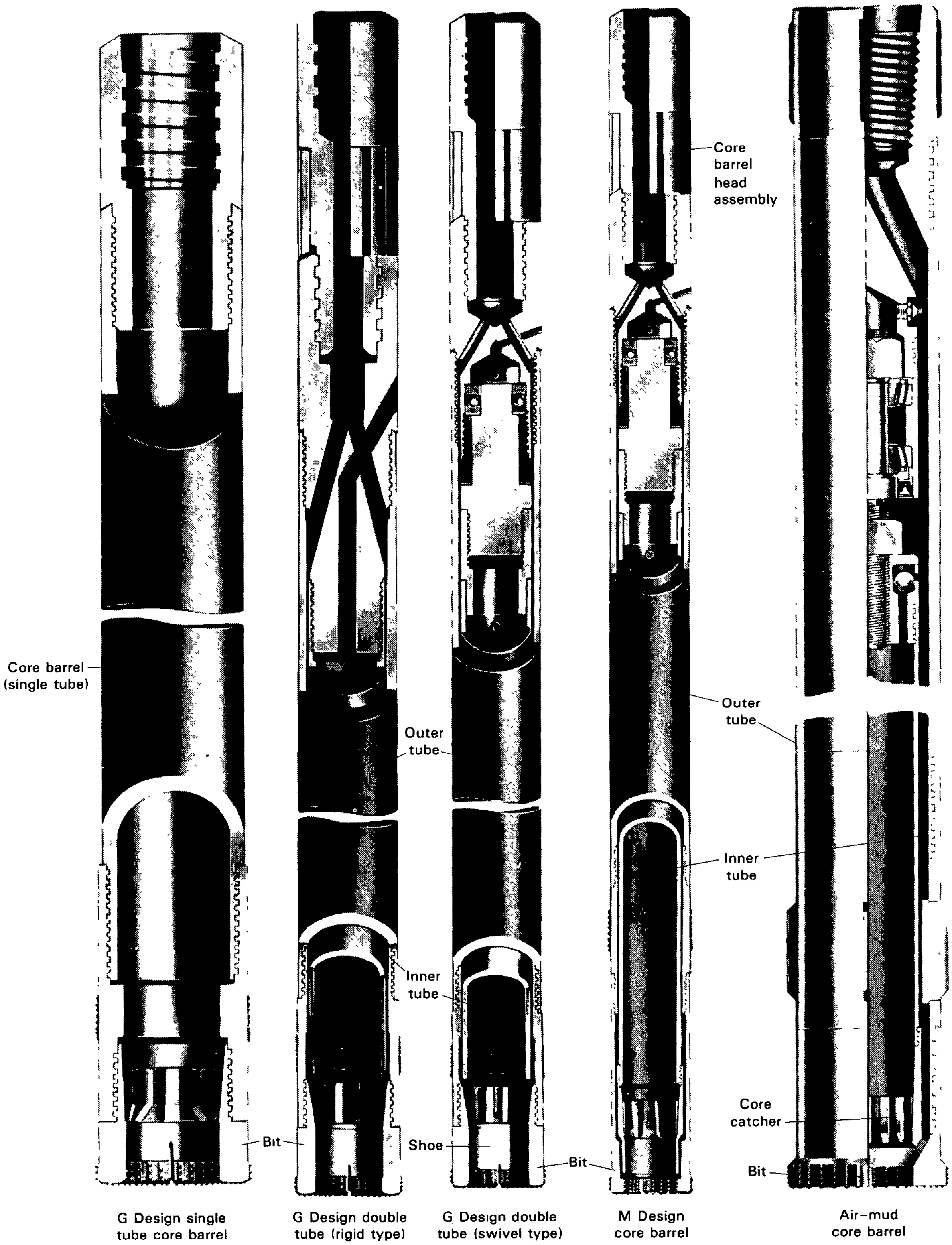


Figure 20.—Typical diamond core barrels (Acker, 1974, reprinted by permission from Acker Drill Co., Inc.).

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.

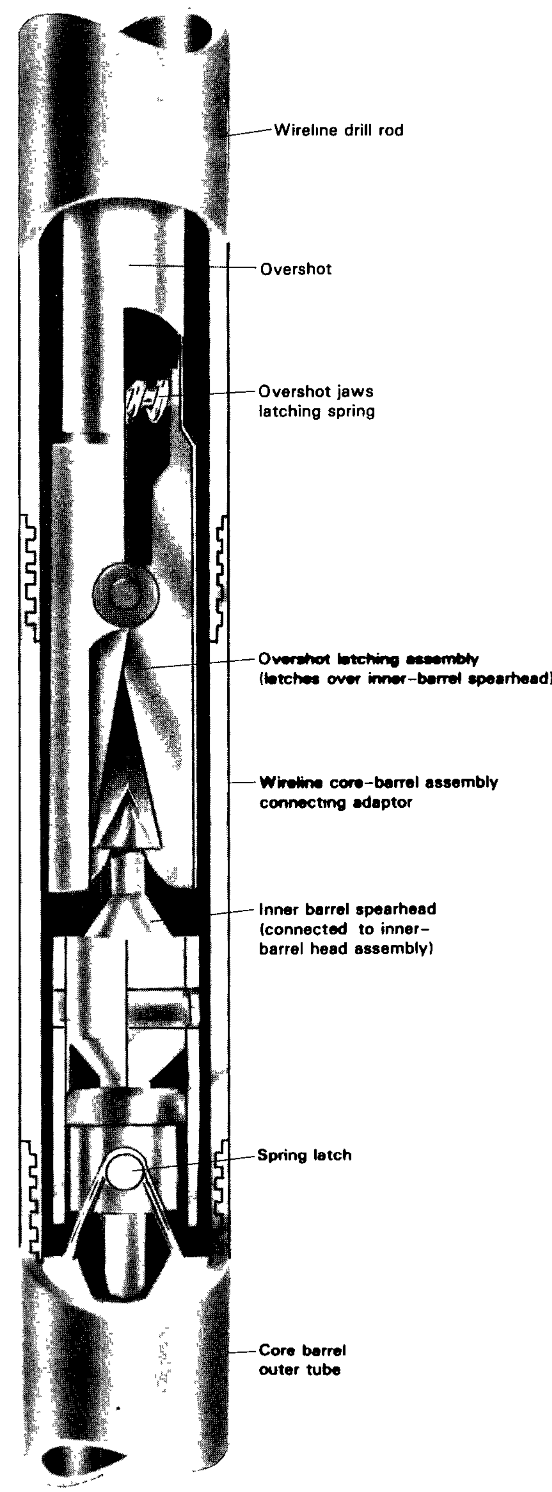


Figure 21.—Wire-line overshot assembly in locked position on inner-barrel head assembly.

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

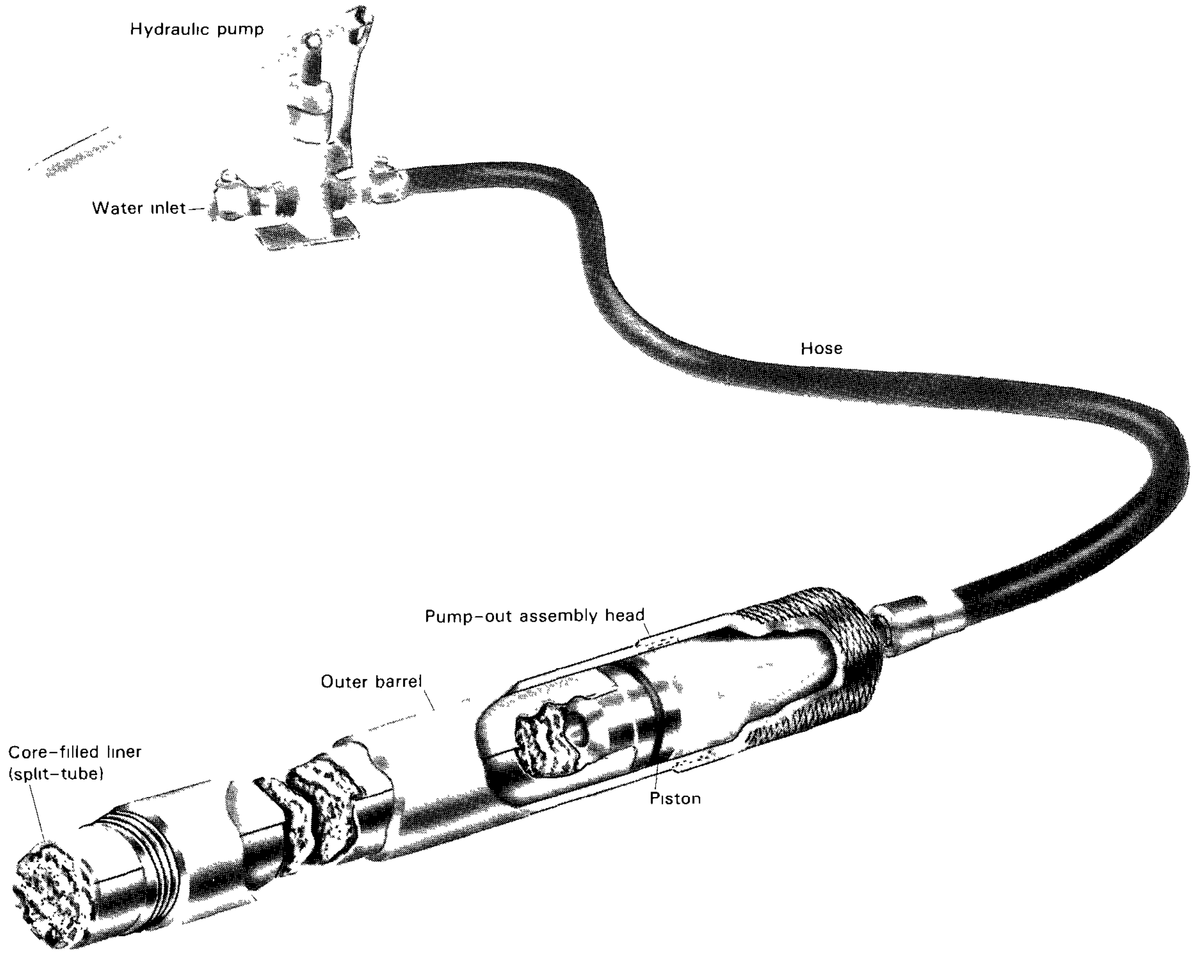


Figure 22.—Core-liner extrusion pump-out assembly (reprinted by permission from Longyear Company).

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.

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.

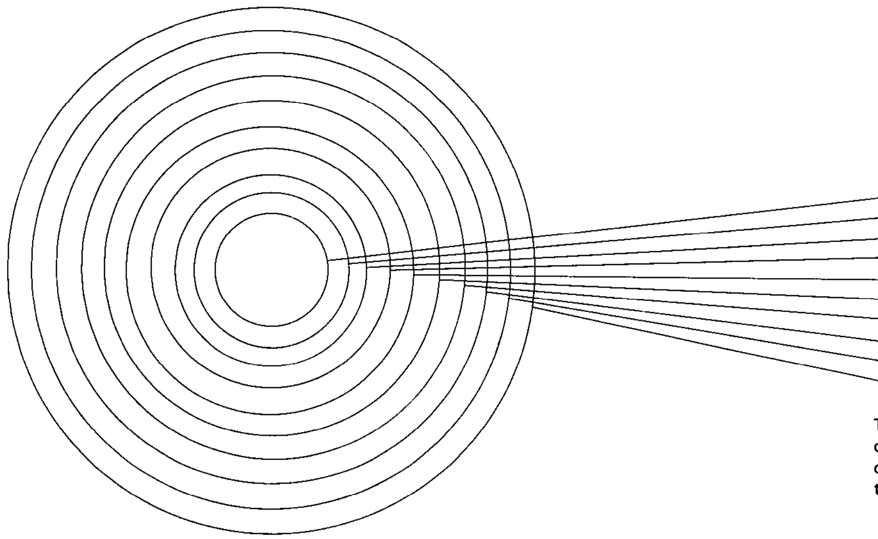
2. The methods suggested in recommendation 1. will often work whenever scoria or cinder zones are encountered in basalts (particularly if one or more of the recommended lost-circulation materials are used in the drilling fluid used for spotting the zone).

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

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



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.

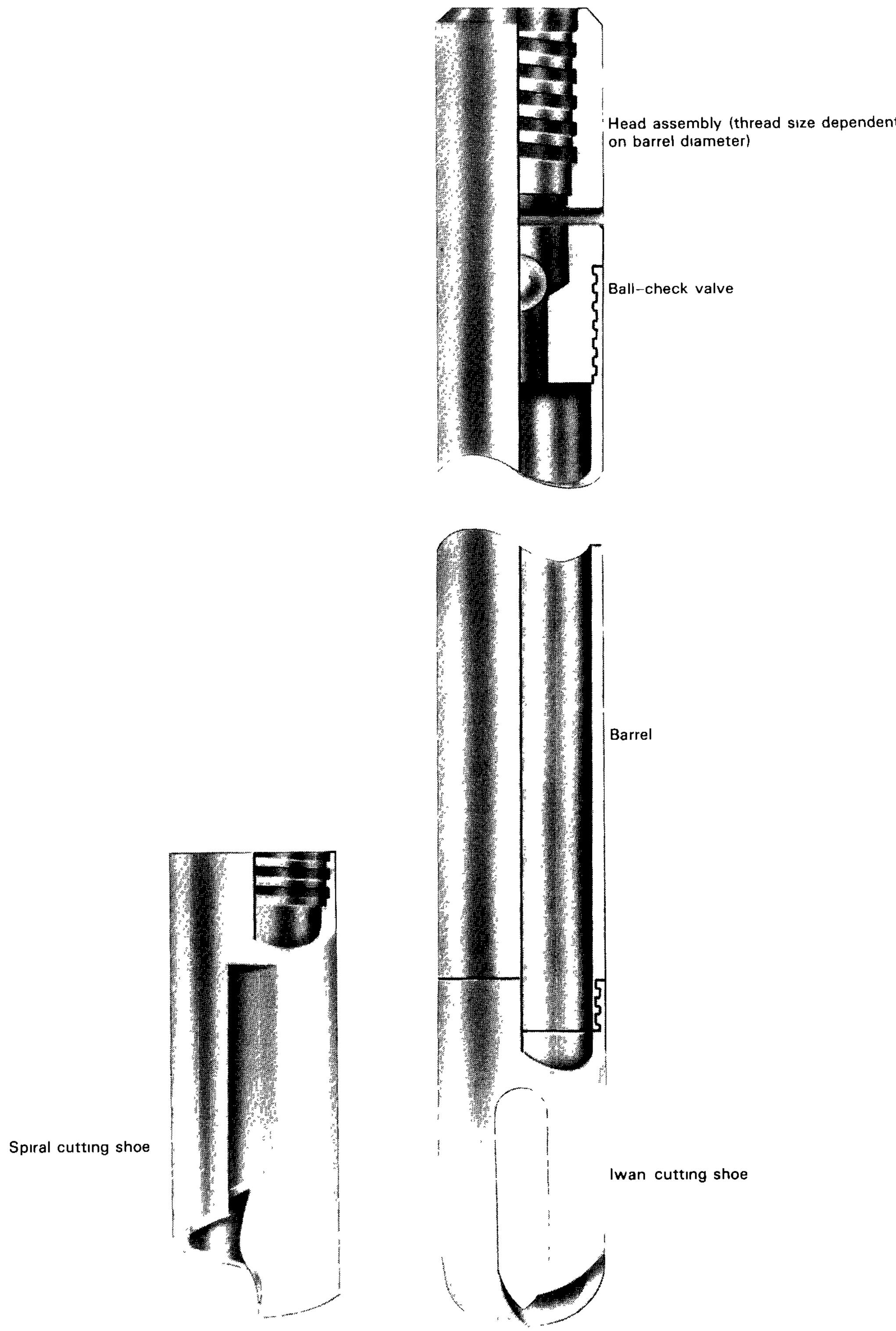


Figure 24.—Spoon sampler and cutting-shoe types.

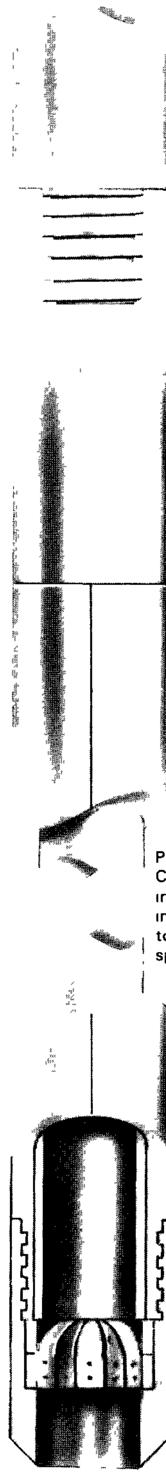


Figure 25.—Split-barrel sampler with liner(s).

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.

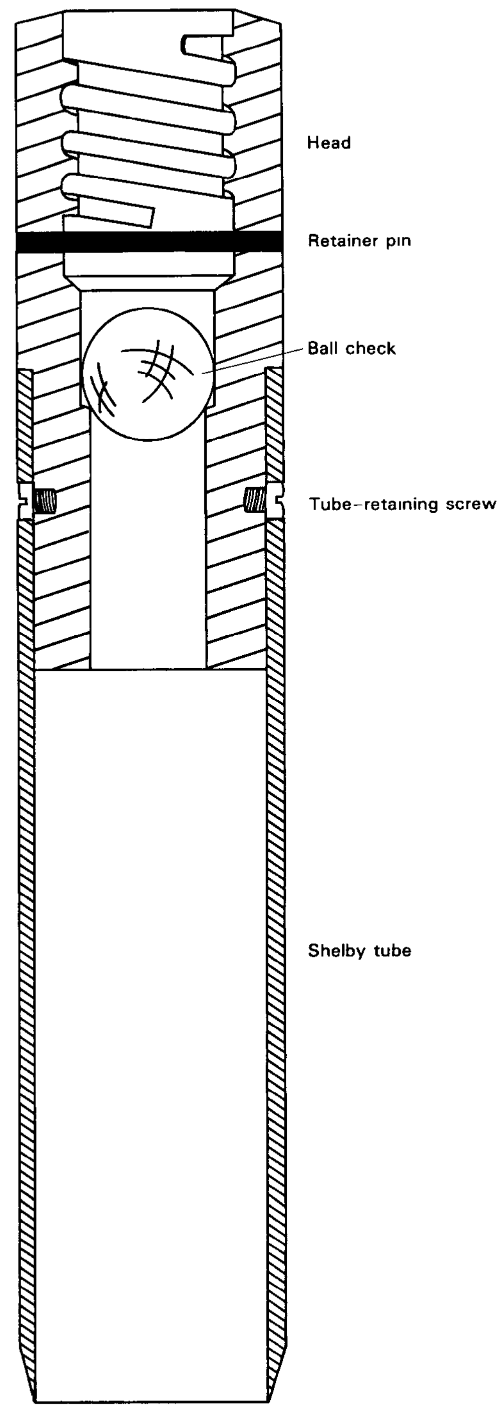


Figure 26.—Shelby-tube sampler.

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;

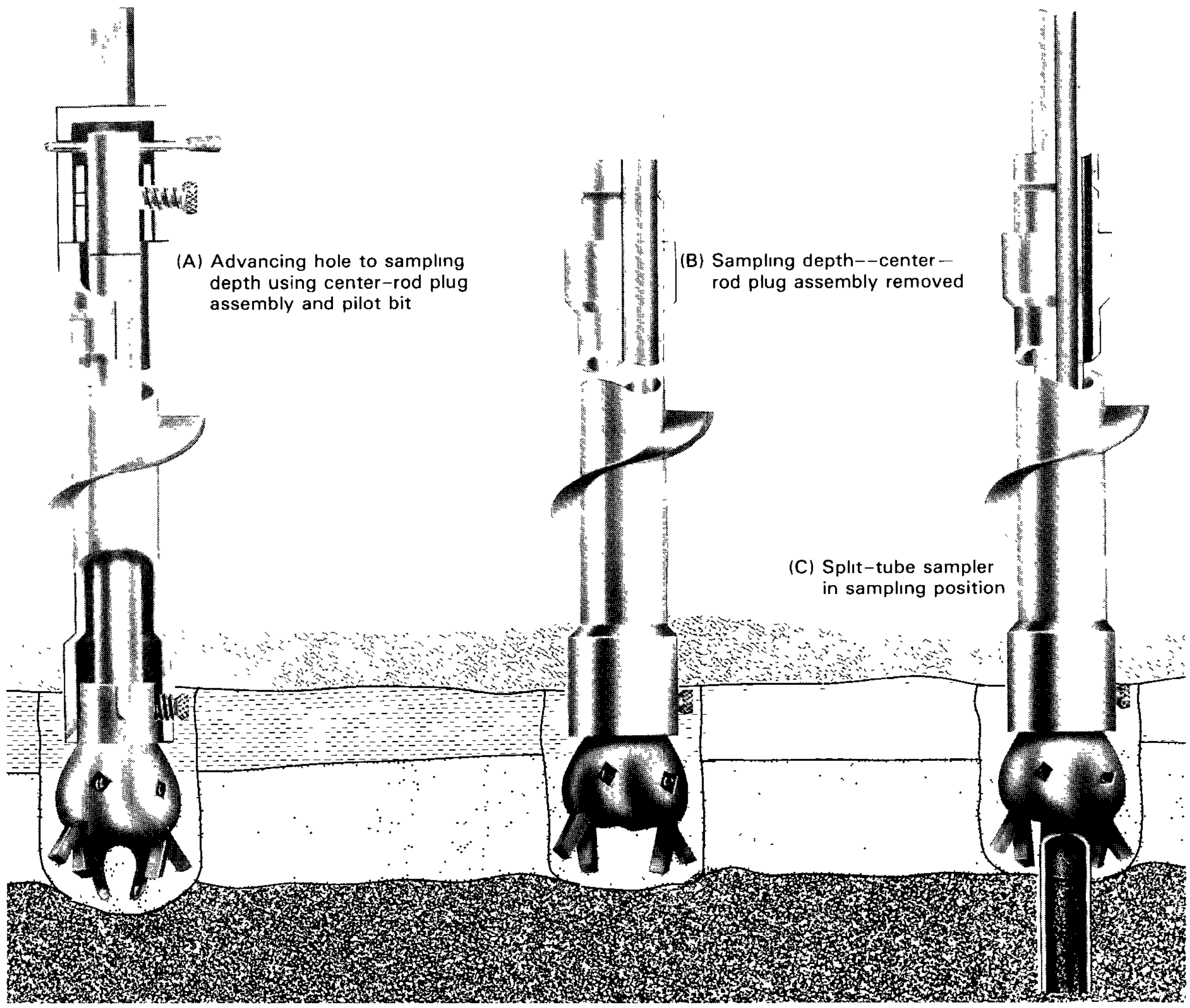


Figure 27.—Soil-sampling technique using hollow-stem augers and split-tube drive sampler.

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

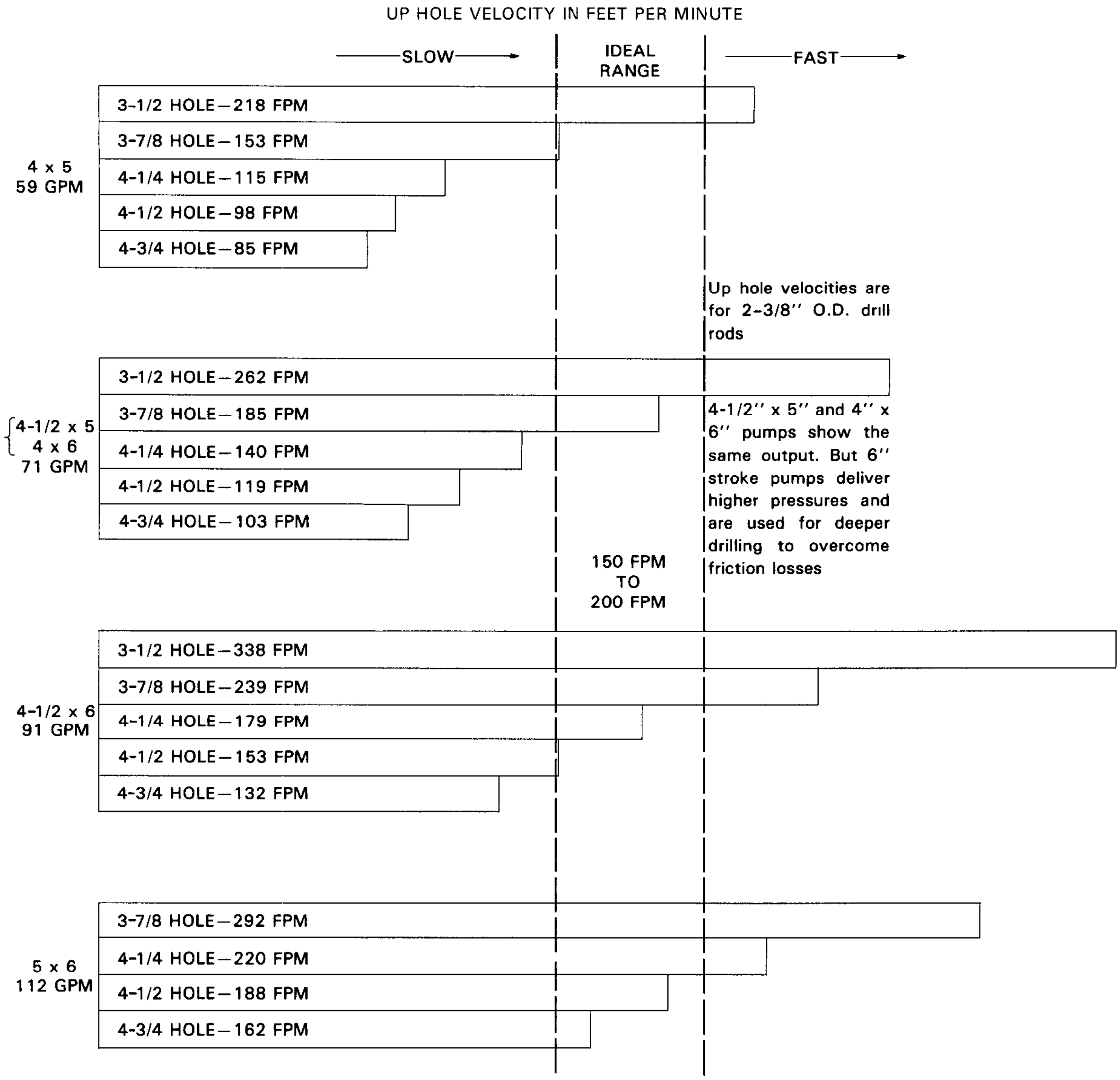


Figure 28.—Cuttings velocity.

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

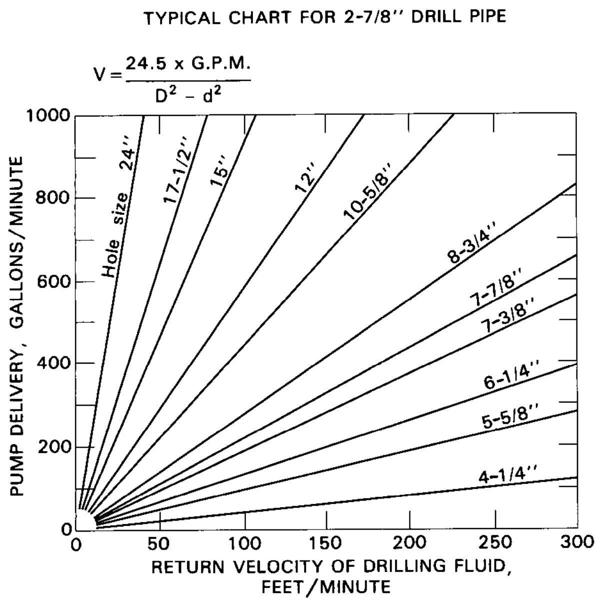


Figure 29.—Pump delivery versus return velocity.

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

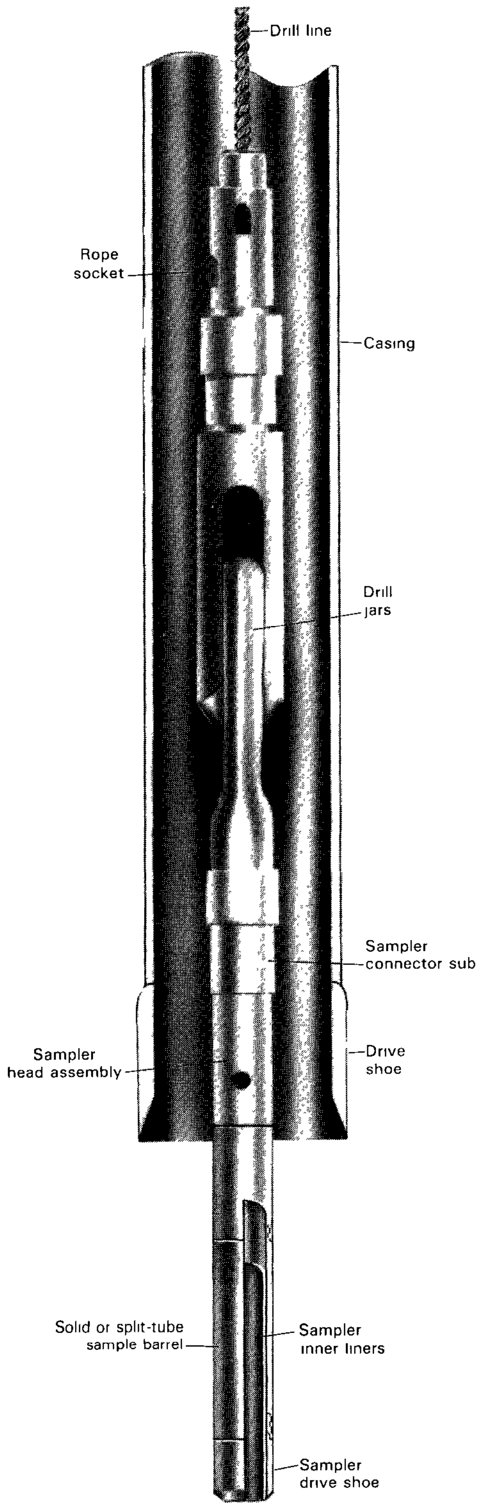


Figure 30.—Cable-tool drive-sampling apparatus.

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