WELL GROUTING AND GROUT SEAL EVALUATION TECHNIQUES

by

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ABSTRACT

Grouting involves placing cement in the annular space between the casing and borehole to provide an impermeable seal between aquifers. Cements are manufactured to accommodate different chemical and physical conditions found in the subsurface environment. Class A, B, and C cements can be used to a depth of 6,000 feet. Class A cement is used when no special properties are required, whereas class B cement is sulfate resistant and class C cement rapidly develops compressive strength. Class G and H cements, used with accelerators or retarders, can meet a wide range of depth and temperature conditions. Additives, can control curing time, density, filtration, viscosity, compressive strength, permeability, shrinkage, and heat of hydration.

Prior to grouting, annular space and borehole temperature and pressure must be determined. Casing centralization and whether to rotate or reciprocate the casing during cement placement should be evaluated. Whether to use a spacer fluid, a cementing plug, or the cement to displace the drilling fluid from the annulus should also be addressed. The volume of grout and method of grout placement will have to be determined.

The location of cement behind the casing can be determined by running a temperature log 6-12 hours after cement placement. Radioactive tracers mixed with the cement can be located by radiation detecting logging devices. The degree of bonding to the casing and the formation, along with channels within the cement, can be verified with a cement bond log and a pulse echo tool.

INTRODUCTION

Much of the ground water pollution that occurs affects the water table and shallow confined aquifers. Also, shallow aquifers may naturally contain undesirable water. It is therefore necessary to take preventive measures so that undesirable water will not contaminate the deeper aquifers. One common path for the interchange of water between aquifers is an inadequately sealed annulus between the well casing and the borehole. In order to protect our vital ground water resources and to provide a long-lasting and environmentally safe ground water supply, the annulus between the casing and borehole must be tightly sealed with an impermeable material. It is imperative that the permeability of the well structure (casing and grout material) be lower than that of the surrounding formations. In addition, the grout seal will protect the casing from corrosive formation water, ensure the structural integrity of the casing, and prevent leaks from defective casing joints.

There are several potential paths for undesirable water to follow in a cemented annulus. One path is through the cement itself. If the cement is improperly formulated or installed, or if it has cracked, the permeability of the cement itself can be high. Still another path can exist between the casing and the grout material. This pathway occurs because of: 1) expansion and contraction of the casing resulting from a temperature increase as the cement cures, 2) shrinkage of the cement, and 3) poor bonding between the cement and the surface of the casing (Kurt, 1983).

Grouting is the procedure of injecting a cementitious slurry into the void space of earth materials to decrease permeability, consolidate them, or increase their strength. Well grouting involves filling the annular space between the well casing and the borehole with a suitable slurry of cement.

CEMENTS

A basic cementing material is classified as one that, without special additives for weight control or setting properties, when mixed with the proper amount of water, will have cementitious properties (Halliburton, 1981). All cements are composed of the same ingredients. The ingredients are tricalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite, and dicalcium silicate. These materials are mixed and put into a kiln to produce a material called cement clinker. The clinker can then be mixed with water to form a cement slurry. By varying the proportions of the ingredients, different cement properties can be attained.

The most abundant ingredient is tricalcium silicate. It determines the compressive strength that the cement will develop. Cements that develop strength rapidly (high-early cement) have a higher percentage of tricalcium silicate than do retarded cements. The setting or thickening time of the cement is controlled by the amount of tricalcium aluminate that is added to the mixture. This cement is, however, susceptible to sulfate attack. To produce a sulfate resistant cement, less than 3 percent tricalcium aluminate is added to the mixture (Halliburton, 1981). The heat given off during hydration of the cement is controlled by adding tetracalcium aluminoferrite, while adding dicalcium silicate to the mixture allows the cement to gain strength over time.

Grout mixtures used for sealing the annular space around a well casing must have certain properties to make them desirable for use. These properties include: 1) low permeability (to resist the flow of fluids through them), 2) capability of bonding to both the well casing and borehole, 3) sufficient strength within a short period of time, 4) inertness, 5) mixability, 6) minimal flow into permeable zones, and 7) safety in handling (Gaber and Fisher, 1988). The grout mixture should have a permeability no greater than that of the least conductive formation penetrated.

Various classes of cements are manufactured to accommodate the different chemical and physical conditions found in the subsurface environment. Cements that are used in well construction are usually manufactured to meet API (American Petroleum Institute) and ASTM (American Society for Testing

TABLE 1--Five API cement classes used in water well construction (modified from Driscoll, 1986)

API classification	Special properties	Recommended range for well depth ft	m
A (similar to ASTM C150, Type I)	None	0–6,000	0–1,830
B (similar to ASTM C150, Type II)	Moderate to high sulfate resistance	0–6,000	0–1,830
C (similar to ASTM C150, Type III)	High early strength	0–6,000	0–1,830
G	Can be used with accelerators and retarders	0–8,000	0–2,440
H	Can be used with accelerators and retarders	0–8,000	0–2,440

Materials) specifications. The API provides specifications for eight classes of well cements, designated classes A, B, C, D, E, F, G, and H. Only classes A, B, C, G, and H are manufactured in the United States. The ASTM acknowledges five types of cement that are used in well cementing. The ASTM types are I, II, III, IV, and V. The API classifications A, B, and C are similar to ASTM types I, II, and III. The API classes G and H are dissimilar to all ASTM types. Table 1 lists the five API cement classes traditionally used in water-well construction.

API Classes A and B

API class A and B cements are commonly called Portland cement. They can be used to a depth of 6,000 feet. Class B is used where a sulfate resistant cement is required. The API recommended water-cement ratio for class A and B cement is 0.46

TABLE 2--Properties of cement slurries (Pers. commun., L. Evans, Dowell Schlumberger, 1984)

API cement class	Slurry weight (lbs/gal)	Mix water required (gals/sack)	Slurry yield (ft ^{3}/sack)	Percentage of mix water by weight of cement
A	15.6	5.20	1.18	46
B	15.6	5.20	1.18	46
C	14.8	6.32	1.32	56
G	15.8	4.97	1.15	44
H	16.3	4.29	1.05	38

(5.2 gallons per sack; 19.7 liters per sack). Laboratory tests indicate that 5.2 gallons of water are needed to hydrolyze one 94-pound sack of Portland cement (Table 2). This mixture produces a slurry of 15.6 lb/gal (pounds per gallon). The proper water-cement ratio provides more effective bridging of the cement particles in the pores of permeable material. This prevents excessive flow of the grout into the formation. In addition, cement shrinkage increases with greater water content because the water is squeezed out of thinner mixtures by pressure against permeable formation materials. To be certain that the correct mixture of water and cement is obtained, it is necessary to weigh the mixture, using a mud balance, prior to placement in the annulus. Because class A and B cements are more economical than the premium cements, they are typically used when no special properties or additives are required.

API Class C

API class C cement can be used to a depth of 6,000 ft and is recommended when high-early strength is important. Class C cement is ground finer during manufacturing and has a greater tricalcium silicate content than class A and B cements. Because of this, class C cement develops a higher compressive strength in less time. The API compressive strength for setting times of 24 and 72 hours at various temperatures for class A, B, and C cements is shown in Table 3. The compressive strength of class C cement is higher than either class A or B cements at curing times up to 30 hours (Halliburton, 1981). The cement should reach a compressive strength of 500 psi (pounds per square inch) before drilling is resumed (Driscoll, 1986). Generally, the 500-psi compressive strength is reached within 24 hours after placement (Table 3). High-early strength cement should be used when better penetration into small crevices and a quick cure are required. The API recommended water-cement ratio is 0.56 by weight (6.3 gallons per sack; 24 liters per sack). This mixture will produce a slurry that weighs 14.8 pounds per gallon.

API Classes G and H

Class G and H cements are used to a depth of 8,000 feet. In addition, they are manufactured so that they can be used with

TABLE 3--Compressive strength and setting time for Type A, B, and C cements (modified from Halliburton, 1968)

Temperature		Borehole pressure		Typical compressive strength							
				24 hours				72 hours			
				Portland		High early		Portland		High early	
°F	°C	psi	kPa	psi	kPa	psi	kPa	psi	kPa	psi	kPa
60	15.6	0	0	615	4,240	780	5,380	2,870	19,790	2,535	17,480
80	26.7	0	0	1,470	10,140	1,870	12,890	5,130	28,480	3,935	27,130
95	35.0	800	5,520	2,085	14,380	2,015	13,890	4,670	32,200	4,105	28,300
110	43.3	1,600	11,030	2,925	20,170	2,705	18,650	5,840	40,270	4,780	32,960

accelerators or retarders to meet a wide range of depth and temperature conditions (Smith, 1976). Class G and H cements are required to meet more rigorous chemical and physical specifications and result in a more uniform product (Halliburton, 1981). The API recommended water-cement ratio for class G cement is 0.44 (5.0 gallons per sack; 18.9 liters per sack) and class H cement is 0.38 (4.3 gallons per sack; 16.3 liters per sack). The slurry weight of class G and H cements are 15.8 lb/gal and 16.3 lb/gal, respectively.

Pozmix Cement

A pozmix cement is an API class A or B cement, a pozzolanic material, and 2 percent bentonite by weight. Pozzolans are any siliceous material that in the presence of lime and water develop cementitious qualities. When class A or B cements are mixed with water, they release approximately 15 percent free lime. The pozzolan combines with the free lime, resulting in a more durable cement. This type of composition is less expensive than other materials and performs well with most additives (Halliburton, 1981).

CEMENT ADDITIVES

Today there are over 40 additives that can be used with API specification cements to control various characteristics of the cement slurry. Additives can affect the characteristics of the cement slurry in several ways. Curing time, density, filtration, viscosity, compressive strength, corrosion resistance, permeability, shrinkage, plasticity, expansion, heat of hydration, and cost can all be controlled by the use of additives. Cement additives are classified as follows: 1) accelerators, 2) retarders, 3) light-weight additives, 4) heavy-weight additives, 5) lost-circulation-control agents, 6) filtration-control agents, 7) viscosity-control agents, and 8) specialty materials.

Accelerators

Cement slurries that are used opposite low-temperature and low-pressure formations, such as those above depths of 200 feet, require accelerators to reduce thickening time and to increase early strength. Calcium chloride and sodium chloride are the most commonly used accelerators. Calcium chloride is normally mixed at 2 to 4 percent by weight of cement. Sodium chloride is mixed with the cement slurry at 1.5 to 5 percent by weight of cement. Sodium chloride does not accelerate the cement to the extent that calcium chloride does; however, it may be used when some acceleration is desired. In as little as four hours, a compressive strength of 500 psi can be developed with the use of accelerators.

Retarders

The temperature of the borehole predominantly determines the rate at which a cement slurry will cure. Generally, as borehole temperature increases the curing time of the cement decreases. The curing time can be controlled by adding a retarder to the cement slurry.

Lignin retarders, calcium lignosulfonate and calcium sodium lignosulfonate, are derived from wood. Lignin retarders are generally used at 0.1 to 1.0 percent by weight of a 94-pound sack of cement (Smith, 1976). Carboxymethyl hydroxyethyl cellulose (CMHEC), a soluble wood derivative, is a highly effective retarder. It can be used at concentrations up to 0.7 percent without the addition of extra water to control viscosity. The range of usage is usually from 0.1 to 1.5 percent by weight of the cement mixture (Shell and Wynne, 1958). The retarding additives most commonly used are not compatible with class A or B cements. API class G and H cements are the only mixtures that should be used with retarders.

Light-weight Additives

Cement slurries will have a weight of approximately 15.6 lb/gal when mixed properly. Formations that have a low fracture gradient cannot support cement slurries of this density. To prevent fracturing the formation, light-weight additives should be added to the cement slurry. The density of the slurry can be reduced by adding water, solids having a low specific gravity, or by both (Smith, 1976). Water should never be increased unless bentonite or a similar material is blended with the cement slurry to absorb the excess water. In a cement column, excess water may collect in pockets, rather than separating and migrating to the top. Excess water produces a weaker cement with a lower resistance to corrosion.

Bentonite added to a cement slurry will decrease the density and thereby increase the volume (Dumbald and others, 1956). Bentonite can be added to any API class of cement in concentrations from 1 to 16 percent by weight of the cement (Beach, 1961). High percentages of bentonite in cement will reduce the compressive strength and increase the thickening time of both regular and retarded cements. Bentonite also lowers the cement’s resistance to chemical attack from formation water. Bentonite should be used only where it is certain that it will remain wet. When bentonite becomes dry, it will shrink and crack, resulting in a microannulus between the casing and grout and between the borehole and grout. It is best to mix the bentonite and water first, then add cement to the clay-water suspension. An additional 1.3 gallons of water is needed for each 2 percent of bentonite added to 94 pounds of cement (Gaber and Fisher, 1988).

Diatomaceous earth can be used for making light-weight cements because it combines with a high percentage of water. Diatomaceous earth produces a slurry with properties similar to those obtained by using bentonite, except that it does not increase the viscosity of the slurry. Diatomaceous earth is less economical and more difficult to use than bentonite (Smith, 1976).

Heavy-weight Additives

When cementing deep wells it often is necessary to offset the high pressures. In order to accomplish this the density of the slurry must be increased. To increase the cement slurry density, an additive should: 1) have a specific gravity in the range of 4.5 to 5.0, 2) have a low water requirement, 3) not significantly reduce the compressive strength of the cement, 4) have very little effect on pumping time of the cement, 5) exhibit a uniform particle size from batch to batch, 6) be inert, and 7) not interfere with well logging (Smith, 1976). Hematite and barite are the most commonly used heavy-weight additives. They meet these physical requirements and have high specific gravity.

Lost-circulation Control

Lost circulation occurs when a formation is fractured and the drilling fluid or cement slurry is lost to the formation. It is necessary to maintain circulation of the drilling fluid through the casing and up the annulus to the surface to maintain the stability of the borehole. Circulating the drilling fluid not only removes solids from the annulus, but it forms a wall cake that supports the borehole wall. There are two steps that are commonly used to combat lost circulation. These steps are 1) decrease the density of the slurry and 2) add a bridging or plugging material to the circulating fluid (Einarsen, 1955).

When formation openings are so large that the sealing agents are ineffective, it becomes necessary to design semisolid or "flash-setting" cements. In this situation, gypsum cement is formulated so that it flash cures. The gypsum cement is circulated down through the casing or drill stem and up the annulus to the zone of lost circulation where it typically cures in less than 1 hour. The disadvantage is that it can cure while still in the pipes or it can become diluted with formation water and be carried away into the formation before it cures.

Filtration Control

The cement slurry must maintain the correct water-cement ratio while it is being placed in the annulus. Pressure from permeable formations will force water from the cement slurry, causing the cement not to develop its desired properties. The water lost from cement slurries to permeable formation materials can be controlled by using additives. The principal functions of filtration-control additives are: 1) form micelles, which control the flow of water from the cement slurry and prevent rapid dehydration, and 2) improve particle size distribution, which determines how liquid is held or trapped in the slurry (Smith, 1976).

Organic polymers (cellulose) and friction reducers are commonly used as filtration-control additives. Organic polymers are used at concentrations from 0.5 to 1.5 percent by weight cement. Dispersants, or friction reducers, are added to cement slurries to control filter loss by dispersing and packing the cement particles and thus increasing the density of the slurry (Smith, 1976).

Viscosity Control

When grouting, the cement slurry should have a viscosity that will achieve the most efficient mud displacement and still permit a good bond between the formation and the casing. By lowering the viscosity of the slurry, the slurry can be pumped in turbulence at lower pressure, thereby, minimizing the horsepower required and lessening the chances of lost circulation and premature dehydration (Brice and Holmes, 1964).

Most slurries are mixed with the amount of water that will provide a set volume equal to the slurry volume without free-water separation. Dispersing agents can be added to the cement slurry to lower viscosity and improve flow properties without changing the set volume.

Polymers and sodium chloride are the two most used dispersants. Polymers are formulated so that they reduce the viscosity while not accelerating or retarding the cement slurry. Polymers are compatible with all API classes of cement except those containing high concentrations of salt. Salt causes the polymer to flocculate, which in turn, causes a rapid increase in the viscosity of the cement slurry (Smith, 1976). Sodium chloride is used to lower the viscosity of slurries containing bentonite, diatomaceous earth, or pozzolan. The sodium chloride, however, will add weight to the slurry and accelerate or retard the cement, depending on the quantity used.

Specialty Additives

Specialty additives are used when standard additives are incompatible with the cement or drilling mud system and when their properties provide unique qualities to the cement. Paraformaldehyde is used as a mud decontaminated when the mud mixes with the cement slurry. Sodium silicate or sodium hydroxide added to the cement mixture will accelerate the curing time, whereas sodium tannate will retard the curing time.

Silica flour added to a cement slurry will increase compressive strength. Clay or ground shale added to the cement mixture will lower the cost of the grout. However, the addition of these substances will lower the compressive strength of the cement (Huntoon, 1989). Plastics can be added to increase the cement mixture's resistance to contamination and increase its ability to penetrate low-permeability materials.

PRE-GROUTING CONSIDERATIONS

Proper well grouting will help minimize one source of contamination of ground water. Time should be taken prior to construction of the well to determine the best cement mixture and grouting method for the geologic environment expected to be encountered. An organized grouting plan will save time and money by providing an adequate grout seal between the casing and the formation in one step. A poorly planned grout job can lead to expensive perforate-and-squeeze operations to seal the areas of the annulus missed because of improper placement of the cement. The following sections discuss the factors that should be considered prior to cementing the casing in the borehole.

Annular Space

The size of the annular space required for grouting depends upon the method used. The tremie pipe method of grout placement, in which the tremie pipe is placed between the casing and the borehole, requires an annular space thickness that is at least 1 inch greater than the diameter of the tremie pipe. The through-the-casing positive placement method of grouting, in which the grout is pumped down through the casing and up the annular space to the surface, requires less annular space than the tremie pipe method. It is recommended that for an effective seal to be obtained and to overcome the hydrostatic pressure produced by the grout flowing up the annulus, the annulus should have a thickness of 3 to 6 inches. The ideal result is a uniform sheath of cement around the casing for the entire vertical distance to be grouted.

Borehole Temperature and Pressure

The temperature and pressure encountered in the borehole determine how well the cement slurry will pump and how well it will develop the strength necessary to support the casing. The temperature of the borehole has the most pronounced effect on the cement slurry. The cement slurry hydrates and cures faster, develops strength more rapidly, and pumping time decreases as the formation temperature increases. In most areas, the formation temperature at depth approximately equals the mean surface temperature plus about 1.5 degrees Fahrenheit per 100 feet of depth. The cooling effect that the drilling fluid has on the borehole can lower the temperature considerably. Pressure from the weight of the drilling fluid will reduce the pumpability of the cement slurry (Smith, 1976).

Formation Fracture Gradient

In unconsolidated formations, problems may be encountered by exceeding the formation-fracturing gradient when cementing the annular space. Fracture gradient is defined as the pressure per foot of depth required to initiate a fracture in a formation. The problem is compounded by the high friction pressure owing to the flow of the cement slurry in the annular space. Gibbs (1965) introduced a method that has produced good results in a number of wells, based on the hole's formation-fracturing gradient. His method is particularly useful where long annular columns are to be filled, or where cement is to be circulated to the surface.

The fracture gradient of a given formation can be measured in several ways. Fracture stimulation is, perhaps, the best source of this information. In fracture stimulation, the pressure reading is taken immediately after the formation is fractured. Many times, however, lost circulation can give a good indication of the fracturing pressure. Fracture gradients for the individual formations encountered are plotted against depth. This plot then profiles the maximum cementing pressure that can be used.

The hydrostatic and friction pressures caused by the cement slurry and the drilling fluid should also be evaluated. The hydrostatic pressure resulting from high slurry weights can in itself exceed the fracture gradient of the formations. Hydrostatic gradient can be calculated by multiplying grout density, in pounds per gallon, times 0.052 to yield pressure, in pounds per square inch per foot of column (Gibbs, 1965). One common source of unexpected pressure is water loss from the cement slurry. Water lost from the cement slurry to permeable formations will: 1) increase slurry density, 2) increase friction, 3) decrease pumpability, and 4) decrease the effective annular seal. With the resulting increase in pressure gradient, the water-loss rate is faster, and the chain of events can sometimes elevate pressures to the point that a weak formation will be fractured (Gibbs, 1965). The use of previously discussed filtration control additives is the most effective way to control this problem.

Backfilling

In cases where an open borehole has been drilled below the depth to which the casing is to be grouted, the lower part of the borehole must be backfilled, or a bridge (cementing basket or formation packer shoe) must be set in the borehole to retain the cement slurry at the desired depth. Backfilling with sand is a common procedure. The sand must be fine enough that cement will not penetrate downward more than a few inches. There is no significant penetration by cement into uniform sand with grain size finer than 0.025 inch, or into non-uniform sand with a hydraulic conductivity less than 250 gallons per day per square foot.

Casing Surface

A rough finish on the outer surface of the casing can increase the hydraulic bond of the cement to the casing. The hydraulic bond strength of the cement to the casing is measured by the ability of the bond to block the migration of fluids in the annulus (Carter and Evans, 1964). Carter and Evans determined that smooth surfaces such as PVC or mill varnished steel pipe had lower hydraulic bond values then the same material after applying a resin-sand coating to the pipe's exterior. In addition, they observed variations in the hydraulic bond strength whenever pipe surfaces were wet with fluids other than water. Pipe surfaces coated with drilling fluid caused a large reduction in the cement-pipe bond. Under this circumstance the pipe that was resin-sand coated provided the higher hydraulic bond. They summarized, the rougher and drier the surface of the casing, the better the cement bond. The practice of using a chemical spacer between the drilling fluid and the cement slurry to remove the drilling fluid and return the casing to a water-wet surface condition will provide a more satisfactory bond between the cement and the casing.

Centralizers

The uniformity of the cement sheath around the casing determines to a great extent the effectiveness of the seal between the borehole and the casing. Owing to the fact that boreholes are rarely straight, the casing will be in contact with the borehole in several places. Proper centering of the casing can be accomplished by using centralizers spaced in critical areas along the casing. When properly installed, centralizers will: 1) center the casing in the borehole, 2) minimize differential sticking, 3) equalize hydrostatic pressure in the annulus, 4) reduce channeling of the cement slurry, and 5) aid in mud removal (Smith, 1976). If the casing is not centered in the borehole, the flow rate on the wide side of the annulus will be greater, where the resistance to flow is the least, than the flow rate on the narrow side of the annulus. This difference in flow rate can cause fluid on the wide side to bypass any fluid on the narrow side, leading to channeling of the cement slurry through the wide side of the annulus.

Tight spots or spots where the casing touches the side of the borehole can also result in channeling (Driscoll, 1986). Channeling of the cement slurry can be avoided by placing centralizers on the casing. Centralizers placed at 20-foot intervals, or one per standard joint of casing, should prevent the casing from contacting the borehole and ensure a uniform thickness of cement around the casing.

Scratchers

Scratchers are wire devices that can be attached to the outside of the casing to break the gel strength of the drilling mud and to aid in removing the filter cake from the borehole wall. There are two types of scratchers: those that are used when the casing is rotated, and those that are used when the casing is reciprocated (Smith, 1976). Rotating scratchers are a high-strength steel wire with angled ends that are welded or clamped to the casing to cut and remove the mud cake during rotation. Reciprocating scratchers are a high-strength steel wire with rounded ends designed to clean the mud cake while lifting the casing up and down. In addition to removing the mud cake, the scratchers aid in creating turbulent flow, that, in turn, improves the cement bond to the casing and the borehole.

Plugs

When the cement slurry is used to displace the drilling fluid, the slurry can become commingled along the interface between it and the drilling fluid. When this occurs the cement will not develop its desired properties. To minimize contamination along the interface, a drillable plug is placed ahead of the cement. This plug displaces the drilling fluid and wipes mud from the casing as it moves down the pipe. The pressure gradient encountered at the bottom of the borehole ruptures the plug, allowing the cement slurry to flow through the plug and up the annular space. A top plug is placed between the cement slurry and the displacing fluid to prevent contamination along the upper interface. The bottom plug is designed to give way to the weight of the cement slurry flowing behind it, whereas the upper plug is designed to withstand the forces of the displacing fluid and provide an adequate seal. The disadvantages of using plugs while cementing include: 1) the plugs are difficult to install during the cementing process, and 2) the plugs do not return up the annulus to remove the filter cake from the borehole wall and to prevent contamination along the interface between the drilling fluid and the cement.

Annular Fluid Displacement

A good primary grouting job requires that the annular fluids be displaced from the annulus and replaced with the cementing fluid. The inadequate removal of the annular fluid may result in a poor cement bond to the formation and casing, which can lead to inter-aquifer communication, pipe corrosion, and pipe collapse. The drilling fluid should be circulated down through the casing and returned up the annulus until a sediment-free discharge at the surface is obtained.

High gel strength, high viscosity, and excessive chemical content of the drilling fluid can cause a poor grout seal to form. Haut and Crook (1979) studied various displacement factors that influenced the cementing displacement process, using a large-scale apparatus that simulates field conditions. The results showed that the condition of the drilling fluid is directly related to cementing success. Thus, many of the common drilling fluids presently being used are not conducive to good grouting practices. Drilling fluids that have high yield points and high gel strengths, while beneficial in maintaining an open hole, become undesirable when grouting. Laboratory tests indicated that decreasing the yield point and gel strength of the drilling fluid increased the displacement efficiency (Clark and Carter, 1972). Mud filter cake characteristics are the most important parameters affecting removal of the mud from the annulus. Simply stated, if mud loses its fluidity it becomes very difficult to displace.

Spacers

A significant problem in cementing is the effective removal of the drilling fluid during displacement. A common practice is to displace the drilling fluid with the cementing slurry; however, many times these two fluids are incompatible. When they become commingled at the interface, a very viscous mass may result which can be deposited for long intervals within the annulus (Crook, Darden, and Watson, 1979). The resulting effect can be a low displacement efficiency of the drilling fluid, contamination of the cement slurry, and inter-aquifer communication. A good practice is to keep the drilling fluid and cementing composition separated to obtain a higher efficiency in drilling fluid displacement and to control contamination of the cementing composition.

Keeping the drilling fluid and cementing composition separated will allow the cement to develop its desired properties. This can be accomplished by injecting a spacer fluid between the drilling fluid and the cement slurry. A spacer fluid may be freshwater, brine, or chemically treated water. The spacer fluid is designed to not only separate the drilling fluid and cement slurry but to control formation pressures, control zones of lost circulation, and protect water-sensitive formations. Spacer fluids have various characteristics depending on the mud system and function. Some contain additives to thin the mud and to penetrate the wall cake. Others contain abrasive materials to scour the hole, and still others have a high viscosity to remove the drilling mud by buoyancy.

The spacer fluid functions much like a piston, and the yield point of the spacer should equal or exceed the yield point of the drilling fluid (Crook, Darden, and Watson, 1979). The spacer fluid will displace the drilling fluid and carry the solids as they are removed from the annulus. A surfactant added to the spacer fluid will aid in displacing the solids and the drilling fluid. The weight of the spacer fluid is important in separating the drilling fluid and the cementing composition. Normally, it is desirable for the spacer fluid weight to be between that of the drilling fluid and that of the cement slurry. The volume of spacer fluid to use must also be considered. A volume of spacer fluid that will give at least 4 minutes of contact time in the annulus is usually sufficient to prevent the spacer fluid from becoming overloaded with solids. For wells deeper than 1,500 feet, the contact time should be increased. The chemicals selected to formulate a spacer fluid must be such that the drilling fluid and cementing composition are not adversely affected.

Most of the drilling services companies offer spacer mixes (also known as flushes) that are available in liquid or powdered form. These "designer spacer fluids" not only help to displace the viscous drilling fluid but they coat the borehole and casing as it passes through the annulus. The cement slurry that follows comes into contact with the coating and quickly gels, forming a strong seal to prevent formation fluids from channeling into the cement. This same seal helps to prevent cement fall-back by holding the cement in the borehole (keeping thief zones from taking the slurry) and by resisting downward flow of the cement.

Grout Volume

After drilling the borehole to the desired depth, a caliper log should be run to determine the configuration of the borehole and as an aid in calculating the volume of cement necessary to grout the casing to the borehole. Table 4 can be used to estimate the volume of grout required to fill the annulus between different casing sizes and borehole diameters. The

TABLE 4--Volume between casing and hole (modified from Huntoon, 1989)

Size of casing (in)	Diameter of hole (in)	Gallons per linear feet	Linear feet per gallon
O.D. 4.5	5	0.1938	5.1600
	6	0.6426	1.5562
	7	1.1730	0.8525
	8	1.7850	0.5602
	10	3.2538	0.3073
O.D. 5.5.	6	0.2346	4.2626
	7	0.7650	1.3072
	8	1.3770	0.7262
	9	2.0706	0.4830
	10	2.8458	0.3514
O.D. 6.625	7	0.2085	4.7962
	8	0.8204	1.2189
	9	1.5140	0.6605
	10	2.2892	0.4368
	12	4.0845	0.2448
O.D 8.625	9	0.2697	3.7078
	10	1.0449	0.9569
	11	1.9017	0.5258
	12	2.8401	0.3521
	14	4.9615	0.2016
O.D. 10.750	12	1.1603	0.8618
	13	2.1803	0.4587
	14	3.2818	0.3047
	16	5.7298	0.1745
	18	8.5043	0.1176
O.D. 13	14	1.1016	0.9078
	15	2.2848	0.4377
	16	3.5496	0.2817
	17	4.8960	0.2042
	20	9.4248	0.1061

volume of grout required can seldom be determined precisely. Irregularities in the size of the borehole, losses to permeable formations, and losses into fractured rock will result in a larger volume of grout used than originally estimated. Because of these irregularities, it is a common practice to have at least 25 percent more grout mixture on site than the volume estimated to fill the annulus (Driscoll, 1986).

Grout Placement

To be certain that the grout will provide a satisfactory seal it is necessary to place it in one continuous operation. Regardless of the grouting method, the grout should be introduced first at the bottom of the borehole. This minimizes contamination, dilution, and bridging of the slurry (Driscoll, 1986).

When placing cement in the annulus the preferred method is to thin the cement slurry so that turbulent flow can be induced at moderate pumping rates. If the cement is pumped under turbulent flow conditions, drilling-fluid removal is enhanced and voids are filled more completely (Haut and Crook, 1979). Turbulent flow offers advantages over non-turbulent flow in that radial components of velocity are present and they exert resisting forces, as well as driving forces and therefore promote displacement of the drilling fluid. Suitable pumps with sufficient pressure should be used to force the grout into the space to be filled.

Graham (1972) conducted an investigation for Humble Oil and Refining Company to choose the most economical and effective cement pumping rate. Graham introduced a technique called rheology balanced cementing (RBC) in which he introduced a new procedure to calculate primary-cementing design criteria on a quantitative basis. Graham found that for most muds and cements effective viscosity decreased as flow rate increased. He derived calculations to take into consideration the relative viscosity difference between the drilling fluid and grout to thereby determine a mobility ratio. Mobility ratio can be related to the optimal flow rate that will displace the drilling fluid with the cementing composition. A mobility ratio of 1.0 or greater is desired. Brice and Holmes (1964) concluded from field studies that if cementing fluids are pumped in a turbulent state for 10 minutes or longer, the probability of a successful primary cementing job increases.

Casing Movement

The casing should be moved, either by rotation or reciprocation, during placement of the grout in order to obtain a higher displacement efficiency of the drilling fluid and better placement of the grout. The casing movement breaks the gel condition of the drilling fluid, which enhances its removal from the annulus (Crook, Darden, and Watson, 1979). The two types of pipe movement were extensively studied by McLean, Manry, and Whitaker (1967). They concluded that when the casing is off center, rotation is more beneficial than reciprocation. If the casing is centered, reciprocation is the better choice. Furthermore, it was determined that a combination of rotation and reciprocation was no more effective on the displacement efficiency of the drilling fluid by the cement slurry than rotation or reciprocation alone. The casing movement should be continued throughout the cementing process. While pumping the cement, the casing movement should be slow as the cement reaches the bottom of the borehole and faster when the cement is in the annulus. If rotation of the casing is the chosen method, the casing should be rotated from 3 to 5 rpm (revolutions per minute). Reciprocations should be on a 2-minute cycle over 15- to 20-foot intervals (Smith, 1976). Reciprocation also causes lateral pipe movement as the centralizers move across borehole irregularities.

Heat of Hydration

As the cement changes from a liquid to a solid, heat is given off (Molz and Kurt, 1979). The heat produced by the cement as it cures can cause the casing to expand. Johnson, Kurt, and Dunham (1980) conducted an experiment to determine the amount of temperature increase that occurs as the grout cures. A 3 5/8-inch grout thickness produced a peak temperature increase of 67 degrees Fahrenheit. In sections where the grout is thicker (borehole irregularities), temperature increases in the range of 170-190 degrees Fahrenheit can be expected. The peak temperatures were normally reached 8-10 hours after water was added to the cement. The higher the formation temperature, the faster is the reaction and the more rapid is the evolution of heat. After the cement has cured, the temperature will slowly return to that of the formation, causing the casing to contract. This expansion and contraction of the casing causes additional stress on the pipe and the cement. This stress can decrease the bond strength and may result in the formation of a microannulus between the casing and the cement.

The ability to dissipate heat depends upon the thermal conductivity and heat capacity of the displacing fluid and the fluid inside the casing (Carter and Evans, 1964). The use of different types of cement and proper cement additives can minimize the problems associated with the heat produced by the hydration of the cement. Adding bentonite to the grout mixture tends to reduce the peak temperature. Other methods of controlling temperature include: 1) adding inert materials, such as sand to the grout, 2) pre-cooling all ingredients, 3) circulating cool water inside the casing, and 4) increasing the water-cement ratio of the grout mixture (Kurt, 1983). While increasing the water-cement ratio decreases the solid mass in the annulus (which in turn decreases the heat of hydration), it also increases the permeability of the grout seal by increasing the amount of shrinkage that occurs as the grout cures.

GROUT PLACEMENT METHODS

There are several methods used to place grout in the annulus. These methods include bailer dumping, gravity filling, displacement, tremie-pipe filling, and through-the-casing positive placement. The positive-placement technique can be by the spacer fluid, two-plug, single upper plug, or continuous-injection method. The author recommends the float-shoe positive-placement method, using a spacer fluid, in almost all circumstances. This method requires less annular space between the casing and borehole and provides the most efficient and effective grout seal.

Bailer Method

The bailer method of grout placement involves lowering the grout material down the annulus to the bottom of the borehole in a bailer and dumping it. Prior to placement of the cement slurry, the drilling fluid should be circulated sufficiently to remove the solids and clear any obstructions in the annular space. The bailer should not be dumped more than 1 foot from the bottom of the hole, and a time of no more than 10 minutes should elapse between dumps. The grout should cure at least 72 hours before well construction is resumed (EPA, 1976). The bailer method should only be used in wells less than 40 feet deep and where there is a minimum annular space of 6 inches. The procedure used to introduce the grout can leave voids and may lead to bridging of the grout material.

Gravity Filling Method

Gravity filling of grout is the method used by many well drillers when installing shallow (less than 40 feet deep) domestic wells. The grout material is uniformly poured from the surface into the annular space without the aid of a tremie pipe. This method should be used only where the interval to be grouted is dry and clearly visible from the surface.

The ability of a cement slurry to travel down an annular space is dependent on several factors: 1) size of the annular space, 2) viscosity and density of the slurry, 3) presence or absence of fluids in the annulus, 4) alignment and continuity of the annulus, 5) rate of pour, and 6) centering of the casing (Gaber and Fisher, 1988). A minimum annular space of 6 inches is required when using this method. Cement slurries are of a relatively high viscosity and do not flow easily by gravity into the small annular space around the casing. Pouring grout slurries through standing fluid promotes dilution of the slurry and separation of the solids. This method of grout placement should be employed with caution and used only for shallow wells where it is certain that contamination from surface runoff does not exist. Voids and bridging commonly occur with this method but can be reduced if the cement is tamped while being introduced into the annulus.

Displacement Method

In this method, a borehole at least 3 inches larger than the casing is drilled to a depth above the interval to be screened. A volume of grout estimated to fill the annulus between the casing and the borehole is placed at the bottom of the well bore. The casing, plugged at the bottom, is inserted into the borehole, displacing the grout up the annular space towards the surface. The buoyancy effect that the grout has on the casing can be overcome by filling the casing with water and pushing the casing with the "pull-down mechanism" on the drilling rig. The grout should cure at least 24 hours before construction is resumed. This method should not be employed for wells greater than 40 feet deep and where water is present in the borehole. If the grout is placed to the bottom of the borehole through a tremie pipe, either with or without pumping, this method may be used to greater depths (but less than 100 feet) and where water is present in the borehole (Gaber and Fisher, 1988).

Tremie Pipe Method

For wells less than 500 feet in depth, grout can be placed through a string of tremie pipe placed outside the casing (Fig. 1). The casing is lowered into the hole with centralizers attached. The centralizers must be aligned along the entire length of the casing so that the tremie pipe can pass by them.

The drilling fluid is circulated through the casing and up the annulus to the surface until a sediment-free discharge is obtained. After circulation is completed, the lower end of the casing is closed with a drillable plug or driven into the borehole bottom so the grout cannot enter the casing. The casing is filled with water to overcome the buoyant force of the slurry. The tremie pipe is lowered down the annulus to within 1 foot from the bottom of the borehole. A minimum annular opening of 3 inches is required between the borehole and the outer surface of the casing (EPA, 1976). The tremie pipe should have a minimum inside diameter of 1.5 inches to decrease the hydrostatic pressure produced by the flowing cement slurry. The spacer fluid and grout are then pumped under pressure down through the tremie pipe and up the annulus to the surface. The position of the tremie pipe should not be changed as the annulus is being filled. In practice the hydraulic head created by the cement typically exceeds the working pressure of the pump. Under these conditions the tremie pipe must be raised periodically, one or two joints at a time, but the bottom of the tremie pipe should always remain beneath the surface of the cement. If operations are interrupted for any reason, the tremie pipe should be raised above the grout level and not be lowered into the cement slurry again until all air and water in the tremie pipe have been displaced by the cement slurry. In boreholes that were drilled into the zone to be screened and had to be backfilled, a slotted pipe, closed at the end, should be

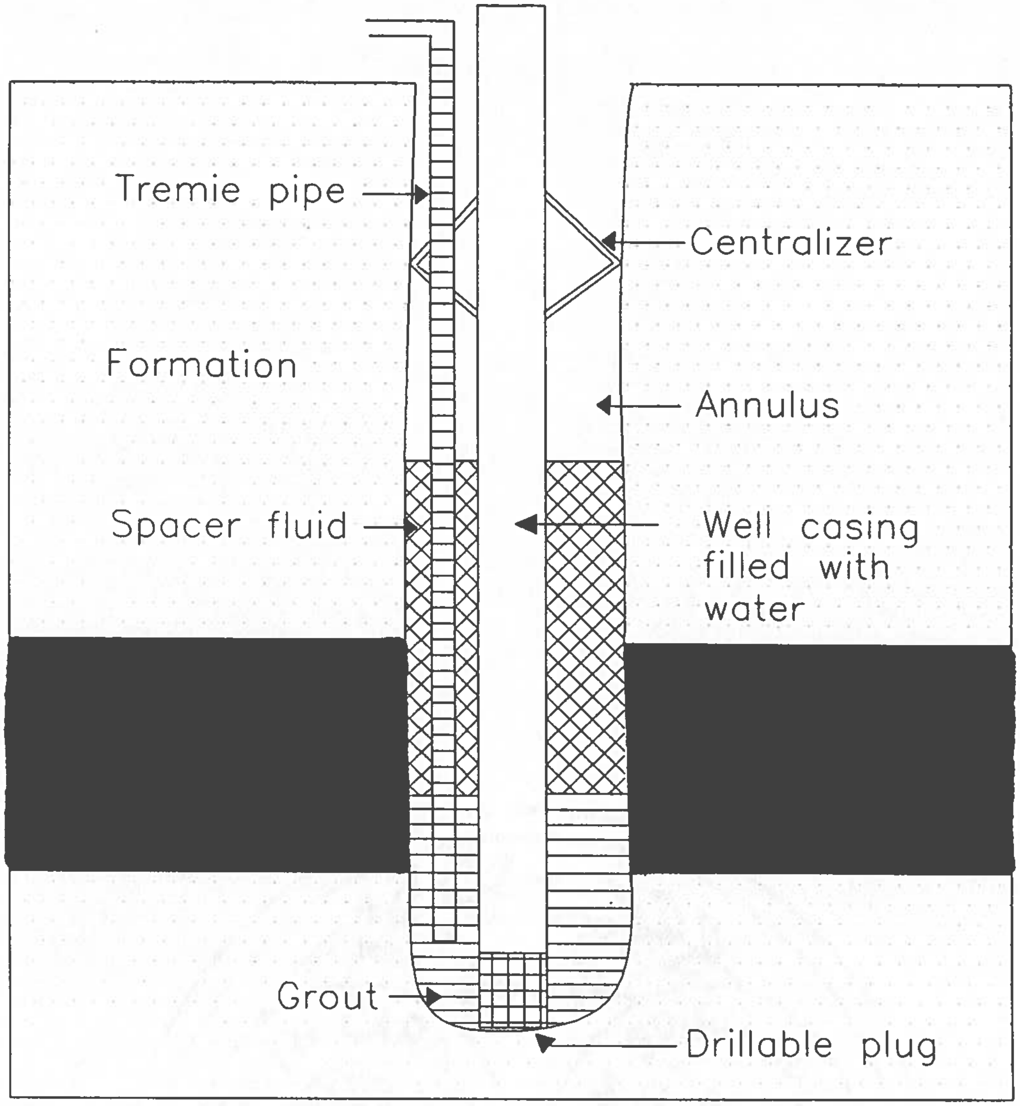

FIGURE 1--Tremie pipe method.

placed on the bottom of the tremie pipe to produce horizontal flow, preventing blowout of the sand during placement of the grout.

Spacer Fluid Positive-placement Method

The through-the-casing positive-placement method of grouting, in which the cement slurry is forced down through the casing and up into the annular space, is one of the better methods for grouting wells (Fig. 2). The use of a spacer fluid in this situation is the recommended method. The casing, with centralizers attached, is lowered down the borehole. The drilling fluid is then circulated down through the casing and up the annulus until a sediment-free discharge is obtained at the surface. A spacer fluid of predetermined volume, weight, and composition is injected in the casing behind the drilling fluid. After weighing the cement slurry with a mud balance, the cement slurry is introduced into the casing on top of the spacer fluid and is pumped until the cement slurry returns up the annulus to the surface. The casing should be reciprocated while the drilling fluid is being displaced from the annulus by the spacer fluid and the cement slurry. The returning cement slurry is weighed, and pumping continues until its weight approaches the weight of the cement slurry prior to injecting it into the casing. At this time a measured volume of water (Table 5) is pumped into the casing to displace the cement slurry. Normally, 15 to 20 feet of cement is left in the bottom of the casing. The water is held in place by closing a back-pressure valve until the grout has cured.

Two Plug Positive-placement Method

In an alternate procedure, two drillable plugs are used (Fig. 3). After circulating the drilling fluid down through the casing and up the annulus to clear any obstructions from the

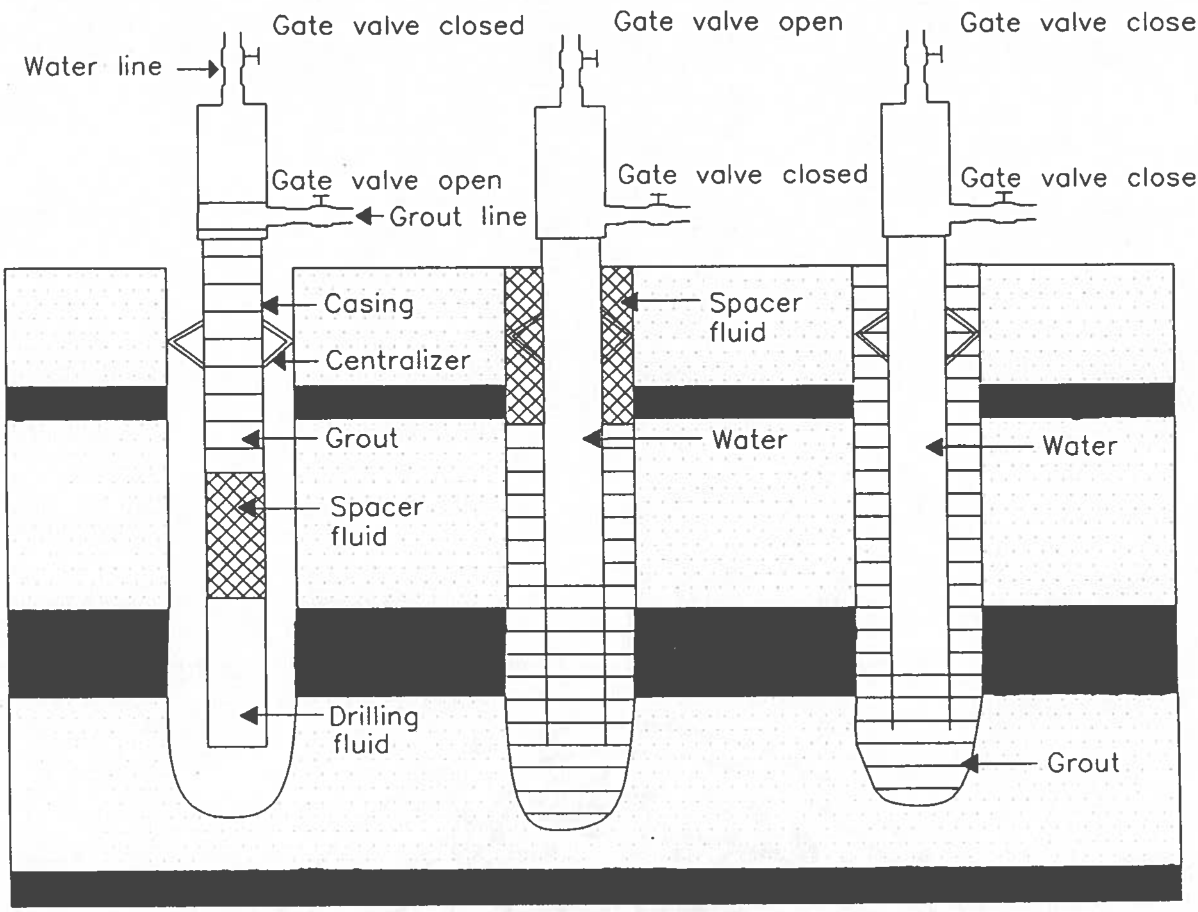

FIGURE 2--Spacer fluid positive-placement method.

hole, the first drillable plug is inserted into the top of the casing, which is then capped with the wellhead equipment. A measured volume of grout (Table 4) is then pumped into the casing. The casing is rotated at 3 to 5 revolutions per minute or reciprocated by lifting and lowering the casing over a 15-foot interval during pumping of the grout, to prevent channel formation and to induce turbulent flow of the cement slurry. The casing is reopened, the second drillable plug is inserted,

TABLE 5--Volume calculation of casing or bore hole (Huntoon, 1989)

Diameter of casing or hole (in)	Gallons per foot of depth	Cubic feet per foot of depth
1	0.041	0.0055
1.5	0.092	0.0123
2	0.163	0.0218
2.5	0.255	0.0341
3	0.367	0.0491
3.5	0.500	0.0668
4	0.653	0.0873
4.5	0.826	0.1104
5	1.020	0.1364
5.5	1.234	0.1650
6	1.469	0.1963
7	2.000	0.2673
8	2.611	0.3491
9	3.305	0.4418
10	4.080	0.5454
11	4.937	0.6600
12	5.875	0.7854
14	8.000	1.069
16	10.44	1.396
18	13.22	1.767
20	16.32	2.182
22	19.75	2.640
24	23.50	3.142
26	27.58	3.687
28	32.00	4.276
30	36.72	4.909

and the casing is recapped. A measured volume of water (Table 5) is then injected into the casing, forcing most of the cement slurry from the casing into the annular space. The water in the casing is held under pressure to prevent backflow of the cement until it has cured. When the cement has cured, the second plug and any cement remaining in the casing is drilled out. Drilling is continued below the grouted section, through the first plug and into the formation. The disadvantage of this method is that the plugs are left at the bottom of the borehole, allowing

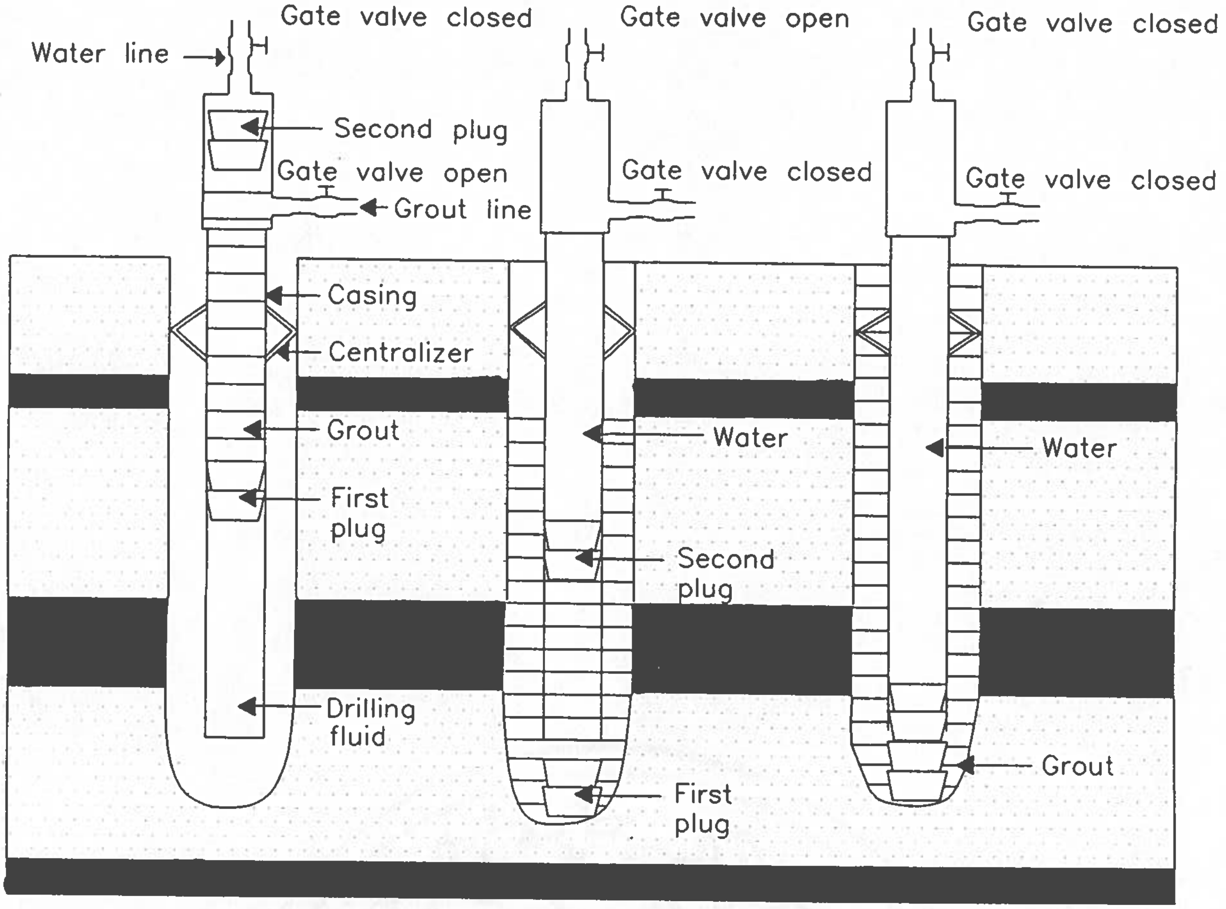

FIGURE 3--Two-plug positive placement method.

mixing of drilling fluid and cement slurry while the two fluids are returning up through the annulus to the surface. Because of the commingling that occurs, the cement slurry must be expelled at the surface until its weight approaches the weight of the cement slurry prior to injection.

Single Plug Positive-placement Method

The single plug positive placement method is a modification of the double-plug procedure and is favored by many drillers.

After following the pre-grouting procedures previously mentioned, a predetermined quantity of cement slurry (Table 4) is pumped into the casing. A single drillable plug is installed in the casing on top of the cement slurry and enough water (Table 5) is added to force most of the cement slurry from the casing out into the annulus. The usual practice is to leave 10 to 15 feet of cement in the casing. In using this method, the part of the cement slurry diluted by the drilling mud must be expelled at the surface until the desired weight of the returning cement slurry is obtained. Doing this produces an uncontaminated grout seal at the upper end of the casing. The use of the plug ensures cement slurry and water separation, resulting in a proper grout seal at the lower end of the casing. Some drillers install a landing collar 10 to 20 feet above the bottom of the casing to eliminate over- or under-displacement of the plug within the casing.

Float-shoe Continuous-injection Method

This recommended technique is one in which the cement slurry is placed by the float-shoe continuous-injection method (EPA, 1976). The bottom of the casing is fitted with a drillable float shoe equipped with a back-pressure valve that is suspended a short distance above the bottom of the borehole (Riewe and Herrick, 1987). An inner string of pipe is run in the casing to the float shoe and connected by a "bayonet fitting", left-hand threaded coupling, or a similar release

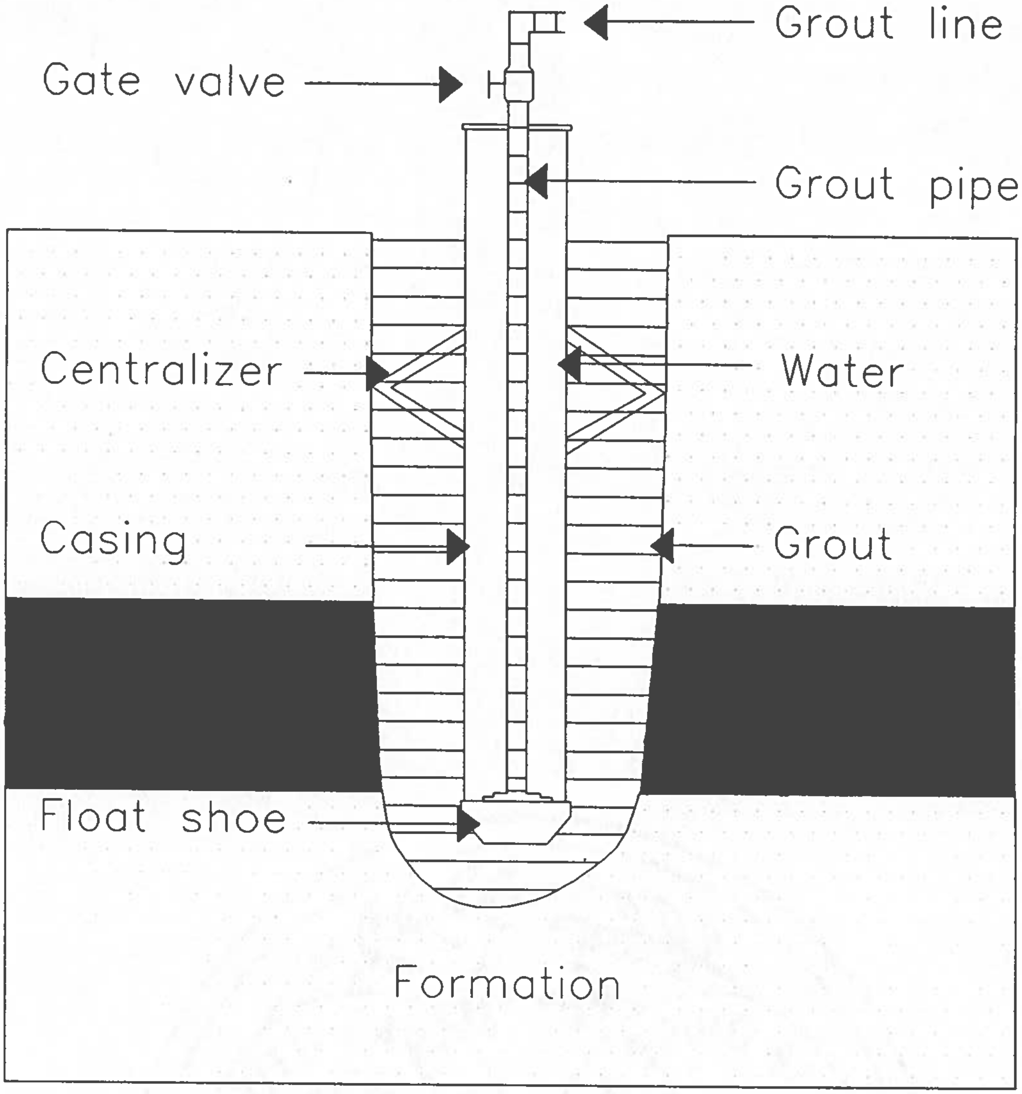

FIGURE 4--Float-shoe continuous-injection method.

mechanism (Fig. 4). Drilling fluid is circulated down through the inner pipe and up the annulus to the surface. When the annular space is clean and open, the spacer fluid and cement slurry are pumped down the inner pipe and forced by continual pumping out into the annular space surrounding the casing. The casing is reciprocated, and pumping is continued until an uncontaminated discharge of the cement slurry is obtained at the surface. Again, this is determined by weighing the returning cement slurry with a mud balance. The inner pipe is then detached from the float shoe and raised to the surface for flushing. After the cement slurry has cured; the float shoe and any grout remaining in the bottom of the casing should be drilled out. The advantages of this method include: 1) reduction in cementing time and the volume of cement required before the cement returns to the surface, 2) reduction in cement required, because displacement is through the small-diameter inner pipe, 3) it avoids having to drill out the cement that occurs within the casing when cementing by the conventional methods, 4) as soon as cement displacement is completed, the inner string can be disconnected and withdrawn from the casing, 5) the casing can be opened at the surface to provide access to circulating cool water inside the casing, and 6) temperature logs and other logs can be run inside the casing for testing purposes.

GROUT SEAL EFFECTIVENESS TESTING

Once the cement has been emplaced the effectiveness of the grout seal should be tested. The cement can be located behind the casing by using a temperature log, a radioactive-tracer survey, or an acoustic cement bond log and pulse echo tool. The acoustic cement bond log (CBL) and pulse echo tool (PET) are used to determine if aquifers are hydraulically isolated by verifying the integrity and bonding of the grout to the casing and borehole.

Temperature Log

A temperature log, run 6 to 12 hours after cementing, can identify the top of the cement and areas of little or no cement by noting anomalies in the temperature gradient. When cement is present behind the casing, heat is liberated. If cement is absent behind the casing the temperature log will record the temperature of the formation. In addition, the temperature log can determine when the grout has cured, by noting when the temperature returns to that of the formation. When this occurs well construction can be resumed.

Radioactive-tracer Surveys

Placing a radioactive material with a short half-life in the cement slurry can aid in determining the location of the cement behind the casing. The two most commonly used tracers are iodine 131 and scandium 46, which have half-lives of 8 and 84 days, respectively. The disadvantages of using a radioactive tracer include: 1) potential health hazard if misused, 2) handling and storage requirements, 3) interference with other radioactive logging techniques, and 4) ground water contamination (Smith, 1976).

Cement Bond Log

The CBL (Fig. 5; tracks 1, 2, and 3) allows for the determination of quality of bond between the casing and the grout and between the formation and the grout, and also the vertical extent of the bonding. The CBL tool consists of an acoustic transmitter and an acoustic receiver. The transmitter generates a sound pulse that travels as a compressional wave by several different paths to the receiver. The three sound waves that arrive back at the receiver, in order, are the casing arrival, the formation arrival, and the fluid arrival. Both the time of arrival and the amplitude of the vibration are used to determine bonding conditions since both the casing and the formation, when acoustically coupled, have characteristic arrival times and amplitudes (Anderson and Walker, 1961). The fluid path is the shortest, but because sound travels slower through fluids it is the last to arrive. The three arrivals are displayed as a seismic spectrum on track 3 of Figure 5. In practice, the fluid arrival is typically masked by the strength of the returning casing and formation arrivals and is seldom seen on the seismic spectrum.

To evaluate the bond between the casing and the cement, you would look at the casing arrival. To evaluate the bond between the formation and the cement, you would look at the formation arrival. The sound travels from the acoustic transmitter through the fluid and strikes the casing, causing the casing to

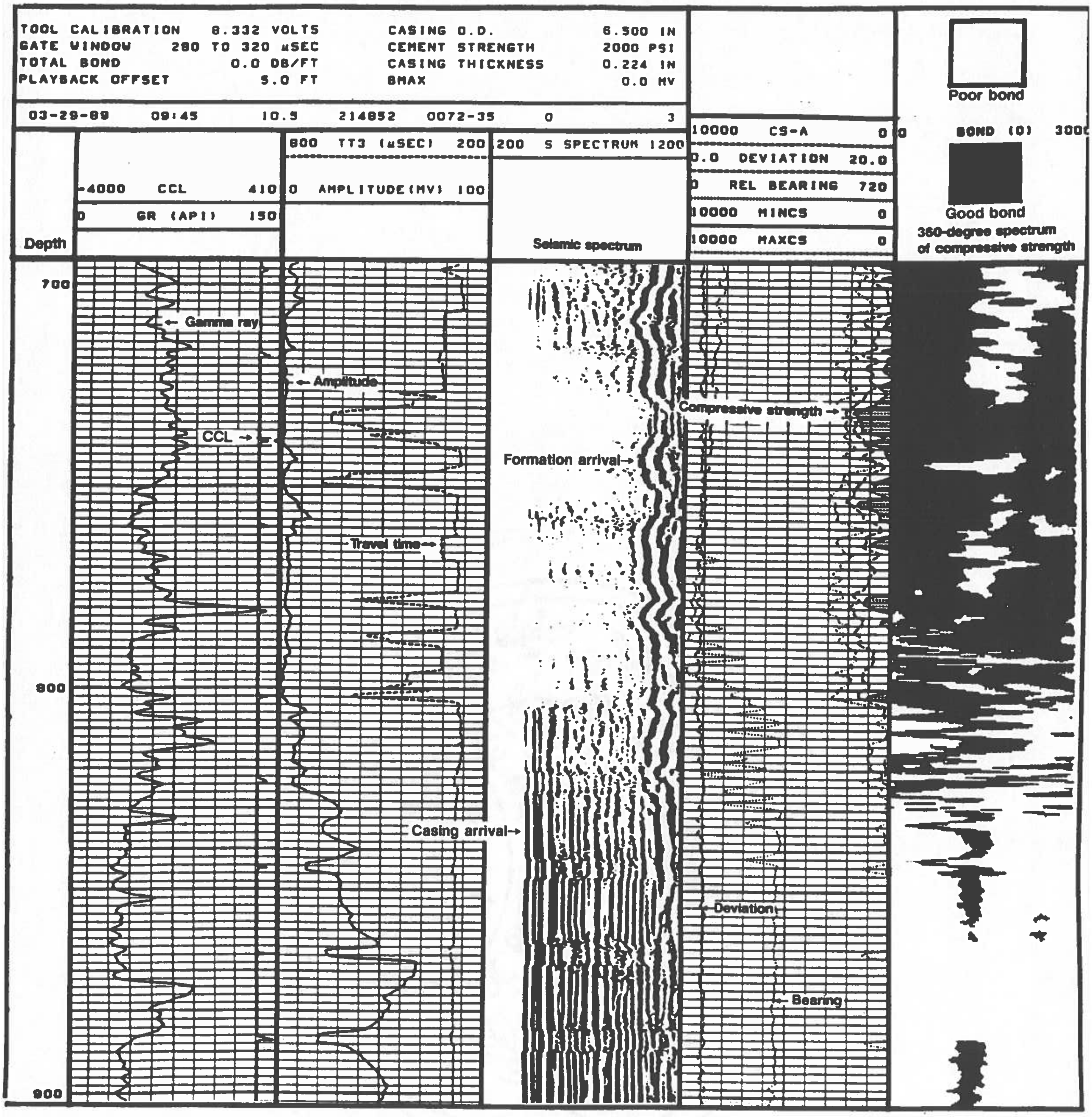

FIGURE 5--Cement bond log and pulse echo tool.

ring. The ringing travels along the casing and back through the fluid to the acoustic receiver. As the amount of cement bonded to the casing is increased, the magnitude of the received signal decreases because the cement impedes the ability of the casing to ring. Because the casing is a smooth surface the reflected sound waves returning to the acoustic receiver are steady and are represented by straight arrivals except for the presence of couplings every 20 feet (see Figure 5). The transmitted sound waves also travel through the casing and cement and are reflected off the formation and back to the acoustic receiver. If continuous cement exists between the casing and the formation, little energy is lost over the round-trip sound path. If no cement is present in the annulus, energy is dissipated in the void spaces. A good bond between the formation and the cement is represented by strong formation arrivals.

Because the borehole wall (formation) is not a smooth surface the reflected sound waves returning to the acoustic receiver are irregular and result in refracted arrivals being displayed on the seismic spectrum. These characteristics of casing and formation arrivals allow for identification on the seismic spectrum. When the cement in the annulus is coupled to the casing and to the formation without fluid boundaries, the casing may be considered "acoustically cemented" and the seismic spectrum shows no casing path and has a coherent formation path similar to that obtained from a sonic log obtained in an open hole (Anderson, Winn, and Walker, 1964).

Figure 5 shows an example of a cement-bond log in which both bonded and unbonded cemented intervals are present. The curves on the CBL from left to right are the gamma-ray, an acoustic casing collar locator (CCL), amplitude, travel time, and the seismic spectrum. The gamma-ray and CCL curves provide depth control. The amplitude curve provides information for evaluating the quality of the cement bond to the casing (low amplitude values represent good bonding). The travel-time curve is used as a quality control for the amplitude curve and as an aid in consolidated rock formations. The third track is the seismic spectrum. This track represents the intensity of the returning signals from the casing and the formation. A well-bonded casing will have little or no signal present on the seismic spectrum. A good formation bond is indicated on the seismic spectrum by strong, refracted, and late arrivals. The interval between 716 and 804 feet represents an interval that has been bonded completely. The low value on the amplitude curve indicates that the casing was not allowed to ring because it was impeded by the cement. In addition, the seismic spectrum indicates that the casing arrivals are weak and the formation arrivals are strong and refracted because of the presence of the cement. The interval between 804 feet and the bottom of the log indicates poor grout bonding. The high value on the amplitude curve, the strong casing arrivals and absence of formation arrivals on the seismic spectrum indicate poor bonding.

Pulse Echo Tool

The PET log (Fig. 5; tracks 4 and 5) uses acoustic signals to measure the compressive strength of the cement behind the casing. The compressive strength is directly proportional to the effective bonding of the cement. The curves on the PET log (track 4) from left to right are the deviation of the borehole, bearing of the tool, and maximum, average, and minimum compressive strength. Track 5 is the compressive strength spectrum. The deviation curve indicates the deviation angle of the casing in the ground. The bearing indicates the rate at which the tool is turning in the hole. The PET utilizes eight pairs of acoustic transmitters and acoustic receivers oriented at consecutive 45-degree angles such that a 360-degree perspective of the hole is presented (track 5) as a compressive strength spectrum. The compressive strength spectrum indicates the quality of the bonding in the annulus. The darker the shading, the better is the bonding. The PET will indicate the presence and orientation of channeling if it exists in the annulus.

Tracks 4 and 5 of Figure 5 are an example of a PET log for the same interval as the CBL. The interval between 716 and 804 feet represents a good bond. The compressive-strength curves within this interval indicate a high compressive strength. In addition, the compressive-strength spectrum is dark, indicating a good bond; however, the light areas indicate that some channeling may exist. The interval between 804 feet and the bottom of the log indicates a zone that was poorly grouted.

SUMMARY

A successful well completion not only requires that the well produce the amount of water desired, but that the grout seal not provide an avenue for entry of undesirable water from zones not intended to supply the well. To accomplish this, the grout's permeability should be lower than the least permeable formation penetrated by the well.

The API has developed design and performance specifications for five classes of cement used in water well construction. Class A cement is used to a depth of 6,000 feet when no special properties are required. It is mixed with 5.2 gallons of water per 94-pound sack of cement to produce a slurry weight of 15.6 pounds per gallon. Class B cement is used to a depth of 6,000 feet when sulfate resistance is required and is mixed in the same proportions as class A cement. Class C cement is manufactured to cure and develop compressive strength rapidly. It can be used to a depth of 6,000 feet and should be mixed with 6.3 gallons of water per 94-pound sack of cement to produce a slurry that weighs 14.8 pounds per gallon. Classes G and H cements are designed to be used with accelerator or retarder additives to meet a wide range of depth and temperature conditions. Class G cement mixed with 4.97 gallons of water per

94-pound sack of cement will produce a slurry weight of 15.8 pounds per gallon. Class H cement mixed with 4.29 gallons of water per 94-pound sack of cement produces a slurry weight of 16.3 pounds per gallon.

To control various attributes of the cement slurry, additives have been developed to be mixed with the slurry. Calcium chloride or sodium chloride mixed from 2 to 4 percent by weight of the cement, can accelerate the curing time to as little as 4 hours. If lost circulation occurs, gypsum added to the cement slurry can produce a slurry that will cure in as little as 1 hour. Lignin, 0.1 to 1.0 percent by weight, can be added to the cement slurry to retard the curing time. Bentonite added to the cement slurry will decrease the density of the slurry, increase the volume, and lower the heat produced during hydration of the cement. Barite or hematite added to the slurry will increase its density. Organic polymers, 0.5 to 1.5 percent by weight of the cement slurry, will control filter loss. The viscosity of the slurry can be controlled by adding dispersing agents to the slurry.

Before grouting, geology and well construction design should be evaluated. The diameter of the annular space must be such that the method of grouting chosen can be implemented. The temperature encountered in the borehole will determine the curing time, the total heat produced during hydration of the cement, and the possibility of casing collapse. Increasing pressures will reduce the pumpability of the cement slurry and may fracture the formation. If a test well is drilled into the zone to be screened, prior to grouting, the borehole must be backfilled to the depth in which the casing is to be set.

A rough outer surface on the casing will increase the bond strength between the cement and the casing. Centralizers placed at 20-foot intervals on the casing, along with movement of the casing during grout placement, will help to ensure that a uniform sheath of cement is placed around the casing and to produce turbulent flow of the cement slurry to aid in breaking the gel strength of the drilling mud. Cementing plugs or spacer fluids placed between the drilling fluid and the cement slurry will prevent contamination along the interface between the two fluids. The volume of grout required will have to be estimated and the placement method must be determined.

The method of placing cement in the annular space between the casing and borehole ranges from pouring the cement slurry from the surface into the annular space to pumping the cement slurry under pressure down through the casing and up the annular space to the surface. The tremie pipe method, where grout is poured or pumped down a small-diameter pipe placed in the annular space, can be used for shallow wells and wells in which the construction design will not allow for the positive-placement technique. The float-shoe continuous-injection positive-placement method of grout placement is the method recommended by the author for almost all other circumstances. In this method a float shoe with a back-pressure valve is attached to the bottom of the casing. The casing is suspended above the bottom of the borehole and an inner string of pipe is attached to the float shoe. The spacer fluid and cement are pumped down through the inner pipe and up the annular space to the surface. The inner pipe is disconnected from the float shoe and raised to the surface.

To determine if the grout program was successful, the cement placement and bonding should be evaluated. The location of the grout behind the casing can be determined by running a temperature log 6-12 hours after placement of the cement in the annulus. A radioactive tracer placed in the cement mixture, can be used to locate the cement by running radioactive logging devices down the well. Channeling and bonding of the cement can be verified by running a cement bond log and a pulse echo tool down the well.

SELECTED REFERENCES

Anderson, W. L. and Walker, T. 1961. Research predicts improved cement bond evaluations with acoustic logs. J. of Pet. Tech. Nov. pp. 1093-1097.

Anderson, T. O., Winn, R. H., and Walker, T. 1964. A qualitative cement bond evaluation method. Drill. and Prod. Prac. pp. 24-32.

Beach, H. J., 1961. Improved bentonite cements through partial acceleration. J. of Pet. Tech. Sept. pp. 923-926.

Brice, J. W. Jr., and Holmes, R. C., 1964. Engineered casing cementing programs using turbulent flow techniques. J of Pet. Tech. May. pp. 503-508.

Carter, L. G. and Evans, G. W., 1964. A study of cement-pipe bonding. J. of Pet. Tech. Feb. pp. 157-160.

Clark, C. R. and Carter, L. G., 1972. Mud displacement with cement slurries. J. of Pet. Tech. July. pp. 755-783.

Crook, R. A., Darden, W. G., and Watson, J. L., 1979. Spacers and their applications in primary cementing. Southwestern Petroleum Short Course. May. pp. 1-7.

Driscoll, F. G., 1986. Groundwater and wells, 2nd Edition. Johnson Division. St. Paul, Minn. 1089 p.

Dumbald, G. K., Brooks, F. A., Jr., Morgam, B. E., and Binkley, G. W., 1956. A light low-water-loss, oil-emulsion cement for use in oil wells. J. of Pet. Tech. May. pp. 99-104.

Einarsen, C. A., 1955. High strength granular sealing material increases efficiency of primary cementing and squeeze cementing. J. of Pet. Tech. Aug. pp. 15-18.

EPA, 1976. Manual of water well construction practices. Environmental Protection Agency. Office of Water Supply. EPA-570/9-75-001. 155 p.

Gaber, S. M., and Fisher, B. O., 1988. Michigan water well grouting manual. Mich. Dept. of Public Health Ground Water Quality Control Section. 80 p.

Gibbs, M. A., 1965. Improve primary cementing by use of hydraulic analysis. The Oil and Gas J. Feb. 3 p.

Graham, H. L., 1972. Rheology-balanced cementing improves primary success. The Oil and Gas J. Dec. pp. 53-60.

Halliburton, 1968. Oil well cement manual. Okla. City, Okla., 68 p.

Halliburton, 1981. Halliburton cementing manual. Halliburton Services. Duncan, Okla. 585 p.

Haut, R. C. and Crook, R. J., 1979. Primary cementing: the mud displacement process. Am. Inst. of Mining, Metallurgical, and Pet. Eng. 12 p.

Huntoon, E., 1989. Removable fact page. Water Well J. v. 43. n. 9. pp. 33-34.

Johnson, R. C., Jr., Kurt, C. E., and Dunham, G. F., Jr., 1980. Well grouting and casing temperature increases. Ground Water v. 18. n. 1. pp. 7-13.

Kurt, C. E., 1983. Cement-based seals for thermoplastic water well casing. Water Well J. v. 37. n. 1. pp. 38-40.

Mclean, R. H., Manry, C. W., and Whitaker, W. W., 1967. Displacement mechanics in primary cementing. J. of Pet. Tech. pp. 251-260.

Molz, F. J. and Kurt, C. E., 1979. Grout-induced temperature rise surrounding wells. Ground Water v. 17. n. 3. pp. 264-269.

Riewe, T. and Herrick, D. 1987. Neat cement grouting techniques. Water Well J. v. 41. n. 7. pp. 34-36.

Shell, F. J. and Wynne, R. A., 1958. Application of low-water-loss cement slurries. Am. Pet. Inst. Rocky Mtn. Dist. Spring Mtg. Denver, Colo. April. Paper 875-12-I

Smith, D. K., 1976. Cementing. Soc. of Pet. Eng. of AIME. Monograph v. 4 of the Henry L. Doherty Series. 184 p.