materials carried in the drilling fluid will cause excessive wear on the bit, drill string, and mud pumps while the drilling rate can be significantly affected. High solids content will result in a thick, sludgy wall cake being deposited on the borehole walls adjacent to permeable formations. If excessive fluid losses are allowed to occur because of poor wall cake condition, borehole stability and other problems—including stuck drill pipe—are risked. Periodic measurement of fluid weight will help avoid potential problems, as well as formation damage resulting from excessive solids being carried in the mud system. Removal of unwanted solids is accomplished by good fluid reservoir design and the use of shale shakers and desander cones.

Field Measurement of Fluid Weight A mud balance is used to measure the fluid weight. The cup on the mud balance is filled to the top with a freshly collected sample of the mud that has been taken from the return, or suction end, of the fluid reservoir. The lid to the mud balance is dropped into place and rotated so that mud is squeezed from the hole in the lid. Excess drilling fluid should be wiped away from the exterior of the mud balance apparatus before balancing the scale. The stand is placed on a level surface. The balance is seated on the knife-edge of the stand and is leveled using the sliding weight. The fluid density is read directly from the inside edge of the sliding weight where it is marked. The cup can be filled with fresh water periodically to check calibration. Fresh water weighs 1.00 kg/L (8.34 lb/gal.).

Optimally, the fluid weight should be kept below 1.08 kg/L (9.0 lb/gal.). Water can be added to thin the fluid and decrease the mud weight. Products, such as powdered barite, can be added to increase the mud weight. Drilling contractors should use a qualified mud engineer to address unusual drilling conditions with specialized drilling fluid programs.

4.4.4.2.2 Fluid Viscosity The viscosity and velocity of the drilling fluid will determine the effectiveness of the removal of drill cuttings from the face of the drilling bit and from the borehole. Viscosity is the resistance to flow of a liguid or gas. In drilling fluids, this is observed as the thickness of the fluid and is a measure of the carrying capacity of the drilling fluid. Low viscosity drilling fluids are preferred for both the effective cleaning of the bit face and borehole, and for the swift settlement of cuttings and solids from the drilling fluid within the circulation reservoirs. However, under special circumstances, it may be necessary to increase the viscosity of the drilling fluid in order to remove large formation particles from the borehole (such as coarse sands and gravel) or to stabilize loose sand and gravel formations. Increased viscosity of the drilling fluid must be countered with the realization that the rate of settlement of solids within the fluid reservoirs will be reduced.

Development of gel strength is associated closely with viscosity in water-based drilling muds (i.e., bentonite drilling muds), which are inclined to thicken, or "gel," when they stop moving. The gel strength of a drilling fluid is the amount of force that is required to break the gel and start it moving again. However, if the gel strength of a drilling fluid is allowed to become too high, excessive mud pump pressure is required to move the fluid. This can cause loss of circulation in the borehole when weak formations are forced to take on large amounts of fluid from the borehole under high mud pump pressure. Rapid gel development will reduce the ability of a drilling fluid to drop its cuttings in the circulation reservoirs. However, when properly controlled, high gel strength is useful for stabilizing troublesome loose sand and gravel formations.

Field Measurement of Fluid Viscosity A Marsh funnel is used to measure fluid viscosity. The funnel is held in an upright position with a finger placed over the outlet as fresh drilling mud is poured through the screen until the level of the fluid reaches the underside of the screen. The drilling fluid sample should be collected from the suction side of the circulation reservoir close to where it enters the borehole. The funnel is held over a one-quart container, and once the finger is removed, the flow is timed in seconds until the one-quart mark is reached in the measuring cup. The number of seconds required to fill one quart is the funnel viscosity. The Marsh funnel can be calibrated using fresh water, which has a funnel viscosity of 26 s at 70°F. The rate at which the drilling fluid gels will affect the viscosity measurement. Because of this characteristic, the Marsh funnel is used for field-testing only and does not replace more accurate measuring devices, such as rheometers or viscometers.

The drilling fluid should remain as thin as possible while still allowing formation stability and retaining its capacity to lift and carry formation particles. The fluid viscosity should be kept at 32 to 38 s for satisfactory performance of the drilling fluid in average drilling conditions.

4.4.4.2.3 Water Loss and Wall Cake Thickness A very important function of the drilling fluid is its ability to form a thin, tough, low-permeability filter or wall cake on the borehole walls. This characteristic will increase borehole stability and allows the drill string and casing strings during installation to move freely, without sticking, within the borehole. A good wall cake will assist in obtaining accurate lithologic information from the borehole by reducing the potential for mixing and cross contamination of samples with other materials found within the borehole.

The drilling fluid, carrying suspended solids, contacts porous formations and allows a bridging of the particles to occur. Tiny platelets of high-quality bentonite clay are deposited in flat layers, which lie tightly against the borehole wall. As the wall cake is deposited, pressure operates as a function of depth (0.433 psi/ft of depth) pressing water from the drilling fluid and leaving behind the thin coating of clay platelets. As successively smaller particles are filtered out of the drilling fluid by the porous formation, only a small amount of liquid is allowed to pass through into the formation and also into the near-well zone. The ability of water to pass through the wall cake is a function of the permeability of the wall cake and the pressure differentials involved. For example, if the wall cake has a very low permeability due to many closely layered platelets, the drilling fluid will not be able to pass through it easily. A wall cake with high permeability typically has misaligned platelets that are not closely layered. This allows drilling fluids to pass through easily, creating high water loss, formation damage, and other problems.

As the borehole is advanced, periodic field tests of the drilling fluid are run (using a small filter press operating at 70,300 kN (70,300 kg-force/m^2; 100 lb-force/sq in. [psi]) to measure the amount of water loss to the formation (Roscoe Moss Company 1990). In addition, it should be noted that a good wall cake permits optimal production from the completed well (following development) by reducing formation damage caused by the drilling fluid.

The texture of the wall cake is an important property. If the wall cake is gritty, additional wear will occur on the rotating components of the drill string, and friction will drag at the drill pipe and bit requiring additional work to rotate the drill string. A gritty wall cake indicates excessive amounts of sand are being allowed to return to the borehole and the circulating reservoirs are not effective in sand removal. Sand returning to the borehole will clog pore spaces and will increase well development time.

Field Measurement of Water Loss A small filter press, using a carbon dioxide cartridge or compressed air, is used to measure water loss and wall cake properties in drilling fluids. The pressure regulator should be set at 100 psi for the test. The pressure vessel should be prepared by placing a disc of filter paper on the screen located at the bottom of the pressure cell. The pressure vessel is filled with freshly collected drilling fluid before placing the cap on top. The pressure vessel then is placed on the frame and held clamped firmly into place and pushing down on the cap of the pressure vessel. A graduated cylinder is placed under the opening at the bottom of the pressure vessel. The pressure regulator is adjusted to 100 psi, and the pressure is maintained for 30 min. The total amount of clear fluid collecting in the graduated cylinder for the 30 min is recorded. (If the test is run for 7.5 min, the result is multiplied by two; however, it is more accurate to run the test for the entire 30 min.)

Field Measurement of Wall Cake Once the test is concluded, the pressure on the vessel must be released gradually by slowly opening the relief valve. Once the pressure vessel has been removed from the clamp and frame, the top of the vessel is removed and the mud remaining within the cup is discarded. The wall cake remaining on the filter paper should be rinsed using a gentle stream of clean water, which will remove any loose mud. The thickness of the wall cake then is measured to the nearest millimeter. The texture of the wall cake should be felt for grittiness, stickiness, slipperiness, or any other characteristic that is observed readily. An effective wall cake should be thin (<2 mm), firm, and slippery, and may be tough enough to peel off the filter paper without tearing. Increasing the ratio of effective colloidal solids in the drilling fluid will increase the thickness of the wall cake.

4.4.4.2.4 Sand Content Excessive sand will create a thick wall cake, cause excessive wear on the rotating components of the drilling system, and cause problems when dropped out of the drilling fluid should circulation in the borehole be interrupted. Measurement of the sand content should be made at frequent intervals during drilling and circulation in the borehole. The sand content is defined as the percentage of solids (by volume) in the drilling fluid that is not able to pass a 200-mesh screen. The amount of abrasiveness due to sand content—and therefore wear on the drilling equipment—is not only a function of particle size but also of hardness and angularity of the particles themselves.

Field Measurement of Sand Content A small sample of freshly collected drilling fluid is added to a special glass vial manufactured by Baroid (1992) to the mark labeled "Mud to Here." Water is added to the mark indicated by "Water to Here." The top of the glass vial is covered and inverted several times to mix before the mixture is poured through a small 200-mesh screen. The resulting fluid is discarded, and the screen is inverted over the glass vial. Clean water is used to rinse the screen back into the glass vial and is allowed to settle until clear water is formed in the tube. The quantity of sand then is read directly from the tube in percent sand by volume of mud. The maximum volume of sand allowed in the drilling mud is 2% by volume. With the reverse rotary drilling method when minimal drilling additives are used, or if Baroid's Poly-Bore product (Baroid 1992) is used, sand content measurements are commonly known to be recorded at less than 1% by volume.

If excessive amounts of sand are found to occur in the drilling fluid, they can be reduced by dilution with water that will reduce the viscosity or by increasing the amount of settling time within the circulation reservoirs by good pit design having adequate baffles or dividers or by the addition of mechanical separation devices, such as shale shakers and banks of desander cones. Good practice dictates that the suction of the mud pump not be allowed to rest on the bottom of the fluid reservoir.

4.4.4.2.5 pH For maximum yield and performance of bentonite drilling mud, the pH of the makeup water must be adjusted to 8 to 9 pH units. Soda ash typically is used to raise the pH, whereas sodium bicarbonate is used to reduce the pH to within the desired range. In the field the pH can be tested using either pHydrion paper or calibrated pH field test meters.

pH of Makeup Water Hard water containing dissolved calcium and magnesium salts will impede the hydration of bentonite drilling muds. If excessive quantities of these compounds occur in the makeup water, it must be treated prior to the addition of drilling additives. For example, soda ash may be used to reduce hardness in the makeup water. Calcium salts seriously impede the hydration properties of the bentonite (reduced viscosity and gel development resulting from inadequate hydration), which will affect the suspension and sealing qualities of the mud system directly. A simple test for calcium in the makeup water easily can avoid the nuisance of fighting poor mud performance. For optimal hydration of the bentonite clay, it is desirable to carry the calcium concentration at less than 100 mg/L.

Excessive chloride concentration in the makeup water will cause increased wall cake thickness and inadequate hydration of the clays resulting in lowered viscosity and gel development. For optimal mud performance, the chloride concentration must be less than 500 mg/L in the makeup water.

Other nuisance situations occurring from the makeup water include strongly acidic water that may require the addition of caustic soda. If sulfides are present in large quantities in the makeup water, the pH may need to be carried at 10 pH units or more to combat corrosion. If the makeup water is highly saline, a specialized drilling fluid program must be implemented, because there are no chemical additives that will remove sodium or potassium salts.

When drilling potable water wells the makeup water must be potable, free from any type of contamination or microorganisms.

4.4.4.3 Common Drilling Problems A common problem that may occur when drilling through thick sequences of heavy clay materials is that of *balling up* the bit. If the bit becomes balled and drilling continues without attempting to correct the situation, premature bit failure may occur if it is not being cooled or lubricated. In addition, when conditions are such as to allow bit balling, the environment is also right to allow the development of *mud rings*. Mud rings are formed when a large mass of highly viscous and plastic drilling fluid has been allowed to build. Mud rings can become so large that they effectively form a packer between the drill string and the borehole wall. When this occurs, excessive pressure may be induced on the formation below, resulting in a loss of circulation condition.

The creation of a thick, sludgy, or highly viscous wall cake causes an increased risk for sticking the drill pipe in the hole or other severe problems. If a zone of thickened and sloppy wall cake has been allowed to form within the borehole and rotation of the drill string halts for even a short time, as when making a connection, *sidewall sticking* can occur. Sidewall sticking is the condition where the drill pipe touches the borehole wall in the area were the thickened wall cake occurs, and the pressure differential effectively pushes the drill pipe into the wall cake. Excessive torque is necessary to free the drill string when this occurs (Roscoe Moss Company 1990).

Another form of stuck drill pipe occurs when circulation is interrupted, and because of the very high solids content of the drilling fluid, the drilling mud begins to thicken and gel within the borehole. When this occurs, it is extremely difficult to resume circulation without washing a tremie down along the drill string in an effort to free it.

Key holing can occur if the borehole deviates from vertical at depth (i.e., forms a dogleg) and a thick buildup of wall cake occurs. Circulation is possible, as is downward movement of the drill string, but upward movement of the drill string is hampered when the drill pipe digs into the convex wall of the borehole at the dogleg.

Sometimes, excessive fluid loss is experienced in what appears to be a complete loss of circulation when no drilling fluid is returned to the surface. This situation results from over-pressurizing the formation at depth due to excessive fluid weight, which drives the available drilling fluid into the formation adjacent to the borehole, rather than allowing it to return up the borehole to the surface.

4.4.5 Reverse Circulation Rotary Drilling

The reverse circulation method of drilling is suited particularly to soft, sedimentary rocks and unconsolidated sand, and gravel formations for the construction of large diameter, high-capacity water-supply wells. As in direct rotary drilling, the walls of the borehole are supported during drilling by the hydrostatic pressure of drilling fluids in the borehole, allowing geophysical logging and well completion to take place in an open borehole. Reverse circulation rotary drilling is used primarily to construct large diameter boreholes appropriate for wells with gravel pack envelopes (Roscoe Moss Company 1990).

As in direct rotary drilling, reverse circulation rotary drilling (see Fig. 4-5) also uses a rotating bit to cut through formation, with the key difference being in the direction of flow of the drilling fluid. In reverse circulation drilling, the fluid reservoir remains filled and connected to the

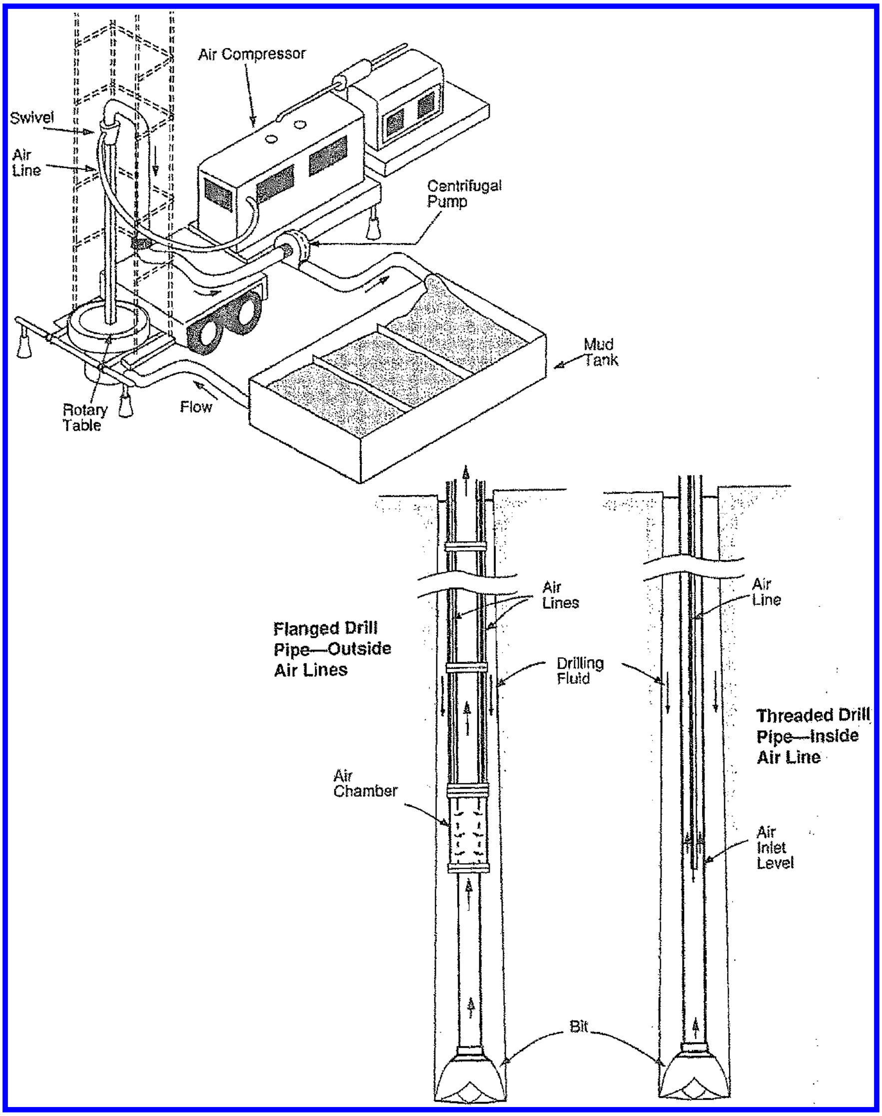

Fig. 4-5. Reverse circulation rotary system components source
Source: Roscoe Moss Company (1990), p. 142; reproduced with permission from Wiley

conductor casing of the borehole by way of a "flow line" (a large diameter hose or pipe). Drilling fluid then flows by gravity through the annular space between the borehole and the drill string and enters the ports in the bit.

A velocity of less than 0.3 m/s (1 ft/s) should be maintained to prevent erosion (or washing out) of the borehole walls due to excessive velocities. Cuttings and fluids are drawn into the interior of the drilling string by airlifting the column of fluid to the surface. The fluid with the cuttings suspended is discharged into large aboveground fluid reservoirs. There, the fluid must remain for a long enough period of time to allow the cuttings to separate from the fluid before it is returned to the borehole. If shaker tables and desanding cones are not used to remove solid materials from the drilling fluid, the baffled reservoirs must be cleaned frequently to maintain volume and the reservoirs' effectiveness in solids removal.

The reverse circulation drilling apparatus is equipped with air compressors to generate the circulation of fluids within the borehole. Pressurized air is pumped into a small diameter pipe, or airline, that hangs within the drill string and bubbles the air to the drilling fluid (Driscoll 2008; Roscoe Moss Company 1990). The air that is forced in the column of fluid causes the column of fluid to become buoyant. This aerated column of fluid will follow the path of least resistance, picking up cuttings with the returning drilling fluid and carrying them to the surface, hence the term *airlifting*.

Some drilling situations require using a drilling fluid system, even with the reverse rotary drilling method. It should be noted that a reverse rotary drilling system that contains only water in the circulation reservoir will develop its own native mud system once the bit begins turning downhole. In formations that contain an abundance of fine-grained materials (i.e., silt and clay), the use of synthetic polymers can be effective in greatly reducing the residency time of the fluid within the circulation reservoir that is necessary in order to separate suspended solids (cuttings) from the liquid drilling fluids.

4.4.6 Other Drilling Methods and Variations

As dictated by differing drilling conditions found throughout the country, many contractors have developed innovative variations of the standard drilling methods to meet the particular needs of their area. A brief discussion of a few of the more well-known drilling methods follows.

4.4.6.1 Bucket Auger Method A bucket auger drilling system consists of either a large-diameter cylindrical bucket that has been fitted on the bottom side with overlapping auger-type cutting blades or a large diameter spiral auger flight. Each type of cutting mechanism is relatively short in length and is approximately 1 m (3.28 ft) in length. The bucket or auger is attached to a kelly that consists of two or more square telescoping lengths of steel. The kelly slides within the center of a circular table and engages a large ring gear, causing the bucket or auger to be rotated. As the bucket or auger cuts into the subsurface materials and deepens the borehole, loosened formation materials are pushed into the bucket or creep up the auger flight. When the full bucket or auger is brought to the surface, it is dumped. As long as the length of the telescoping kelly can accommodate the depth of the borehole, the bucket or auger flight can be brought to the surface where it dumps its load of cuttings without the need to disconnect components. If the auger progresses more deeply than the kelly can extend, drill rods must be included to add length, and these lengths of rod must be removed every time the bucket is brought to the surface to dump cuttings (Driscoll 2008).

The bucket auger drilling method has been used to drill wells up to 76 m (250 ft) in depth in weakly consolidated but stable formations. However, more shallow wells of 16 to 46 m (50 to 75 ft) in depth are more common. In more consolidated formations, the auger blades can be fitted with durable tungsten carbide inserts to grind and cut through harder materials. However, boulders and cobbles must be fished from the borehole by an orange-peel bucket, stone tongs, or a ram's horn tool. The bucket auger drilling method works best in areas of clay deposits, because this is the type of formation that can withstand the excavation without excessive caving, even in areas with high static water levels. When drilling in sandy or loose deposits, water and bentonite gel may be added to maintain an open borehole by increasing the hydrostatic pressure within the borehole and by creating a wall cake to support the borehole walls. When using the bucket auger drilling method in formations that have shallow groundwater, it is typically difficult to maintain an open borehole without the addition of bentonite drilling mud. The bentonite mud helps coat the walls of the borehole and reduces water loss to the formations, keeping the borehole from caving (Driscoll 2008).

4.4.6.2 Dual Tube Methods: Rotary and Percussion A variation on cuttings removal in air rotary and percussion systems is the dual tube method. In this closed circulation system, dual wall drill pipe is used to convey air to the bit where it picks up available cuttings and then lifts them to the surface. Water mist is used as the fluid and passes through the annulus between the walls of the inner and outer pipes, through openings in the bit face, and then up the inner tube, carrying cuttings to the surface. Because water or drilling fluid contacts the walls of the borehole only in the immediate vicinity of the drill bit (where cuttings enter the system), reliable formation samples that are disturbed but unmixed can be collected as drilling progresses. This method is used primary in environmental drilling situations where large cobbles and boulders preclude the standard environmental drilling methods but can be used for municipal water supply, especially in areas with difficult drilling conditions. However, the casing and borehole diameters typically are limited to

150 mm (6 in.), or less. Some contractors are known to carry larger sizes of dual-wall drilling pipe and can accommodate larger borehole and casing diameters.

4.4.6.2.1 Dual-Tube Reverse Air Circulation Method The dual tube (also known as dual wall) reverse air circulation drilling method uses double-walled drill pipe in which the outer wall of the drill pipe is flush-threaded. An airtight double O-ring seal achieves the connections for the inner barrel of the drill string. Short connector sections containing the O-rings slip over the ends of the inner barrel of the drill pipe at each threaded connection of the drill pipe. This completes the continuity of the inner barrel from the drilling bit to the top head drive unit. Within each section of drill pipe, the inner barrel is held in place by centering guides. A top head drive unit provides rotational power to the drill string while a hydraulically operated injection pump is used to introduce water to the stream of air that is being forced down the annular space between the walls of the drill string (see Fig. 4-6).

With the dual wall reverse circulation drilling method, a roller cone bit with intermeshing teeth is used when drilling alluvial or unconsolidated materials, an insert bit (having tungsten carbide chips imbedded in its face and outer ring) is used for denser or more tightly compacted materials, and a down-the-hole hammer is used for well-consolidated materials, such as bedrock. A special drill bit adaptor is fabricated to form a skirt over the body of the bit that catches and directs the cuttings up the inner barrel. This type of bit sub also permits the borehole to be advanced with minimal clearance between the drill string and the borehole wall (typically 1/4 to 1/2 in., maximum). The drill pipe supports the tight borehole, eliminates leakage by the tight fit and allows uncontaminated sampling to occur.

The drilling fluid (consisting of only air and water) flows through the drill string by reverse circulation. All air and fluid is contained between the walls of the drill string and is in contact with formational materials only at the face of the drilling bit. The definition of reverse circulation is that the flow of air and fluid is downward through the annulus (in this case between the inner and outer walls of the drill string rather than in the open borehole) and then upward through the interior of the drill string to be discharged at the surface.

At the face of the drilling bit, loosened rock fragments and groundwater (when present) are picked up by the returning flow of air carried through the inner barrel of the drill string. These materials then are discharged directly to a cyclone separator. The cyclone separator reduces the velocity of the returning air and material so that rock fragments and groundwater drop by gravity from the bottom of the cyclone, through a