William C. Lyons

Air and Gas Drilling Manual

Applications for Oil and Gas Recovery Wells and Geothermal Fluids Recovery Wells

Third Edition

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Applications for Oil and Gas Recovery Wells and Geothermal Fluids Recovery Wells

Third Edition

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Preface

This third edition of the *Air and Gas Drilling Manual* is written as a practical reference for engineers and earth scientists who are engaged in planning and carrying out deep air and gas drilling operations. The book covers air (or gas) drilling fluids, aerated (gasified) drilling fluids, and foam drilling. Further, from the mechanical rock destruction standpoint, the book covers conventional rotary drilling, downhole positive displacement motor (PDM) drilling, and down-the-hole hammer (DTH) drilling.

The first edition of this book was published in 1984 by Gulf Publishing Company of Houston, Texas. It was written primarily for the oil and gas recovery drilling industry and had moderate success, selling out of the initial printing by the late 1980s. The second edition was published by McGraw-Hill in 2001; it added a significant section on the shallow geotechnical drilling industry (e.g., water wells, environmental monitoring wells, mining ventilation shafts, etc.), and also discussed shallow reverse circulation, dual wall drill pipe, and air hammer technologies.

This new third edition is unique in that we have presented the entire engineering material in both the USCS and SI unit systems, including the important equations used for air (or gas) drilling and aerated (gasified) drilling, along with the foam drilling calculations. Solutions based on these equations are given in MathCad™, using both USCS and SI units, providing readers with complete transparency into the solution process for these complicated fluid flow problems. These MathCad™ solutions are presented in the appendices.

The authors would like to thank the editors and staff at Elsevier Science and Technology Books and especially Senior Acquisitions Editor Ken McCombs and Production Project Manager Anne McGee. Their support and assistance during the preparation of this manuscript were invaluable.

The authors would also like to thank the technical staff of the underbalanced drilling group of Weatherford International for their continued support of our efforts to prepare this manuscript. We particularly appreciate the continued encouragement of Jim Stanley.

We encourage engineers and scientists in industry and practice to comment on this book. We also apologize for any errors that might be still lurking in the manuscript. We know our book is not perfect, but we also know that this edition is now complete.

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CHAPTER

1 Introduction and Units

Air and gas drilling technology accounts for approximately 30% of the world's land oil and gas drilling operations. The technology is limited to use in mature sedimentary basins. Mature sedimentary basins are older basins that have competent subsurface rock formations that are cemented and are usually uplifted with little formation water remaining in them. Although modern air and gas drilling technology began in the United States in the 1930s, it is presently being used in drilling operations throughout the world's many oil and gas producing geologic provinces. It is important at this time in the development of this technology that the basic principles of the technology be communicated in a manner that all drilling personnel will understand.

Engineers and drilling supervisory personnel need to make predictive calculations in order to make their drilling operations efficient and cost-effective. The prediction calculations for air and gas drilling technology are complicated and will require the creation of calculation computer programs. There are sophisticated air and gas programs available commercially. However, in the tradition of most engineering fields, once the basic outline of the program has been determined, we tend to hand the "care and feeding" of the program over to the computer science department. The authors have chosen to use MathCad™ as our tool to communicate to the readers the details of how air and gas drilling predictive calculations are made. These MathCad™ solutions are very transparent and are written in a sequence that we would do by hand.

The detailed MathCad™ solutions are given in the appendices and the results are summarized in each applicable text chapter. The solutions are presented in both USCS units and SI units. It is assumed that newcomers to this technology will eventually make the choice of whether to use an existing commercial program or to develop their own company internal program.

1.1 OBJECTIVES AND TERMINOLOGY

The objective of this professional text is to familiarize the readers with the basic terminology and operational applications of this new field of air and gas drilling technology. The use of this technology is limited to land drilling operations. There are three subcategories of this technology: (1) air and gas fluids drilling, (2) aerated fluids drilling, and (3) stable foam fluids drilling. This technology is utilized by the industry to fulfill two specific drilling objectives.

Performance Drilling: This type of drilling takes advantage of the low annulus bottom hole pressures that accompany the use of this technology. Low annulus bottom hole pressures usually result in higher rates of penetrations. This type of drilling operation is applied in the upper portions of a well bore above the potential producing reservoir formation. The specific objective of this type of drilling is to drill more rapidly through the upper formations above the reservoir and to ultimately reduce the cost of a drilling operation.

Underbalanced Drilling: Here again, this type of drilling takes advantage of the low annulus bottom hole pressure characteristic of the technology. Underbalanced drilling uses the various bottom hole pressure capabilities of air and gas, and aerated and stable foam drilling fluids to drill into potential reservoir rock producing formations with annulus bottom hole pressures lower than the static reservoir pressure. In this manner, the reservoir fluids flow to the well bore as the drill bit is advanced through the reservoir. Underbalanced drilling operations attempt to avoid damage to the reservoir rock formation so that the reservoir will produce effectively through its life.

1.2 ENGINEERING CALCULATIONS AND UNITS

Modern engineering practices can be traced back to early eighth century AD with the tradition of the “master builder.” This was the time of the creation of the measure known as the Charlemagne foot. From the eighth century into the seventeenth century a variety of weights and measures were used throughout the world. It was not until the Weights and Measures Act of 1824 that a complete British Imperial System (BIS) was codified within the British Isles, British Commonwealth countries, and in some of the former colonies of the British. The United States actually did not accept the full BIS. The United States made use of some of the major units within the system and some of the older units that had evolved through the years of colonialism before 1824. This evolution of usage within the United States ultimately became the United States Customary System (USCS) (units that are still in common use today).

The development of some of the basic units that ultimately became part of the present-day System International d’Unites probably began around the time of Louis XIV of France. This system is simply known today as SI units (or metric units). This system became codified by international treaty in France in 1875. Most unit systems today, including the British Imperial System and the USCS, are referenced to the actual existing weights (mass) and measures of the SI units.

These reference weights and measures are kept in Paris, France, for all nations and other entities to utilize. Since 1875 the SI units system has gained rapid and widespread use throughout the world. This system is characterized by its consistent set of units and simplicity of use. SI units are based on multiples of decades or units of tens. All basic weights and measurement units within SI are in increasing magnitudes of multiples of 10, 100, 1000, etc. Nearly all other unit systems in use in international trade and commerce around the world today must be referenced against the SI standard units before they are considered legitimate for legal matters or for international commercial trade.

1.2.1 Physical Mechanics

There are important fundamental definitions of units that must be used to define any units system. These are as follow:

Force is the action of one body on another that causes acceleration of the second body unless acted on by an equal and opposite action countering the effect of the first body.

Time is a measure of the sequence of events. In Newtonian mechanics, time is an absolute quantity. In relativistic mechanics, it is relative to the *frame of reference* in which the sequence of events is observed. The common unit of time is seconds.

Inertia is that property of matter that causes a resistance to any change in the motion of a body.

Mass is a quantitative measure of *inertia*.

This monograph deals exclusively with Newtonian mechanics. Newton's general laws are as follow:

Law I. If a balanced force system acts on a particle at rest, it will remain at rest. If a balanced force system acts on a particle in motion, it will remain in motion in a straight line without acceleration.

Law II. If an unbalanced force system acts on a particle, it will accelerate in proportion to the magnitude and in the direction of the resultant force.

Law III. When two particles exert forces on each other, these forces are equal in magnitude, opposite in direction, and collinear.

Note that the aforementioned original definitions of the just-defined laws by Newton were conceived around the concept of force.

1.2.2 Basic Units and Usage

The USCS is a *gravitational* system, as its units of *length, force*, and *time* (i.e., *L, F,* and *T,* respectively) are considered fundamental dimensions of the system and all other units, including *mass*, are derived. The SI is an *absolute* system, as its units of *length, mass*, and *time* (i.e., *L, M*, and *T,* respectively) are considered fundamental dimensions of the system and all others units, including *force*, can be derived.

The reason for this distinction between *gravitational* and *absolute* is the laudable desire that the concept and magnitude of the mass of an object should remain the same regardless of where it is with respect to other objects that would influence it through gravitational attraction. In this manner, the SI would be in accordance with Newton's universal gravitation, which describes the universality of gravity (Newton's universal gravitation is an extension of Newton's general Law II given earlier). The average force of gravitational attraction is shown mathematically in Newton's universal gravitation by

$$F_{gravity} = G\frac{m_1 m_2}{d^2}, \tag{1-1}$$

where $F_{gravity}$ is the gravitational attraction force (lb, N), G is a constant of proportionality (3.437×10^{-8} lb-ft^2/slug^2, or 6.673×10^{-11} N-m^2/kg^2), m_1 is mass 1 (slug, kg), m_2 is mass 2 (slug, kg), and d is the distance between the masses (ft, m).

Newton's Law II can be written as

$$F = ma, \tag{1-2}$$

where F is the force being applied to a mass near the Earth's surface (lb, N), m is any object mass (slug, kg), and a is the resultant acceleration of that mass as a result of the applied force F (ft/sec^2, m/sec^2).

If a mass is on or near the Earth's surface, the force of attraction of the mass to the Earth's mass becomes the special force denoted as weight (assuming that no other forces act on the mass). In this situation, the acceleration term a becomes g, which is the gravitation acceleration of the mass falling freely toward the Earth's center. Substituting g into Equation (1-2) and letting the F terms in Equations (1-1) and (1-2) equal each other, g becomes

$$g = \frac{Gm_{earth}}{d^2}. \tag{1-3}$$

Substituting the respective unit system values, Earth's average mass at midlatitudes, and the distance between the center of the Earth and the object near the Earth's surface gives the acceleration term that is used in most practical engineering mechanics problems. Table 1-1 gives the values of g for both USCS and SI. The high accuracy values are given with the commonly used engineering values.

Table 1-1. Acceleration of Gravity

	g (precision)	g (engineer)
USCS (ft/sec^2)	32.1740	32.2
SI (m/sec^2)	9.8067	9.81

Note that the Earth is not a perfect sphere and, therefore, the acceleration of gravity will be slightly different depending on whether the free falling body is at a pole or at the equator. The elliptical form of the Earth dictates that the acceleration of gravity will be slightly greater at the equator than at the poles. For most engineering applications at or near the Earth's surface, the average acceleration of gravity (engineer) terms is used for calculation purposes. Both of these calculations were made using the exact same calculation method. No special term or constant was employed to obtain either of the aforementioned results.

The objective of the third edition of this monograph is to allow engineers and other technologists to carry out the required air and gas drilling calculations in both USCS and SI units. In particular, the objective is for engineers and technologists who presently use the USCS units to learn to be comfortable using SI units. Most examples discussed within this monograph are steady-state flow problems. To facilitate this objective, two minor alterations in SI common usage have been made by the authors to allow for a more unified method of calculation manipulation that are common to the usage of USCS units. This will allow for transparency in the manipulation of both systems that practitioners working in both systems will recognize.

Nearly all equations in this monograph are derived for use with any consist set of units. Further, because most equations in the edition are for steady-state flow, the equations will have few mass (m) or gravity acceleration (g) terms. Therefore, the first alteration from traditional SI usage will be that any SI data or terms that contain *kg* units are to be changed to force units (N) by multiplying appropriately by 9.8 m/sec^2. An example of this first alteration would be the writing of power in SI units as N-m/sec (watt) instead of the SI purist form of the power unit of kg m^2/sec^3 (which is also a watt). The second alteration from traditional SI use will be that fluid flow pressure will be given in *N/cm*^{2} instead of the more SI purist recognized pascal (N/m^2). Regarding the latter alteration, it is very difficult for either the USCS or the SI practitioner to visualize the force per unit area magnitude being applied with pressure to the inside flow area of a 2-in (*50.8 mm*) nominal diameter pipe or applied as stress to a small machine part when the area of the pressure or stress unit is many times greater than the area of the actual flow area or stress area. Therefore, as is done in the USCS for most applications where a pressure or stress in lb/ft^2 is converted to lb/in^2 (psi), the pascal (*N/m*^{2}) will be converted to *N/cm*^{2}.

In essence, the authors recommend analyzing the SI system just like the USCS in that both are treated as an F, L, and T system, instead of treating the SI as an M, L, and T system. Even though this logic may annoy the SI purist, it will be shown that employing the SI mass concept (and the USCS force concept) in this manner is far superior to employing the cobbled-up unit conversions that define force and mass in the USCS as lb_f and lb_m, and the use the associated artificial constants g_c and g_o [2]. The authors have even seen this conversion concept applied to SI units in the form of N_f and N_m with their associated artificial constants g_c and g_o.

It is suspected that this misguided conversion creation was developed by chemical and mechanical engineering professors who were motivated by the desire to have a heat transfer equation that is rationally in consistent force

Table 1-2. Units that Define Mass [1]

Unit System	Mass Unit	Dimensions
USCS	Slug	F T^2/L = *lb sec²/ft*
SI	Kilogram	F T^2/L = *N sec²/m*

(weight) units to correct to mass based equation [2]. Since specific heat c_p in the SI is in units of *kcal/kg-K* and in the USCS is in units of *BTU/lb-^oR*, a heat transfer equation for SI calculations would have to be in mass rate of flow $\dot{m}$ and a heat transfer equation for the USCS would have to be in weight rate of flow $\dot{w}$. It is our contention that for those of us who were not brought up using the SI as our primary system of units, it is easier for engineers to carry out calculations in both systems if both unit systems are manipulated in exactly the same manner. This requires use of the kilogram definition given in Table 1-2. It is likely that this kilogram definition will "ruffle the feathers" of some SI purists.

There is one other important change to be made in the application of the SI to the drilling calculations made in this monograph. *N/m^2* or the *pascal* (*Pa*) as a pressure unit will not be used. Most engineers have trouble correlating these values to small cross-sectional areas such as a 2-in nominal pipe (~i.d. of 2.0 in, or 50.8 mm). In its place we will use a pressure term unit of *N/cm^2*. It is only necessary to multiply this pressure unit by 10^4 to obtain pressure in *pascals* or by 0.6897 to obtain psi. The convenience of using this alternate SI pressure term is illustrated by Figure 1-1, where both scales can be placed easily on the same gauge face for easy reading (and reference to one another).

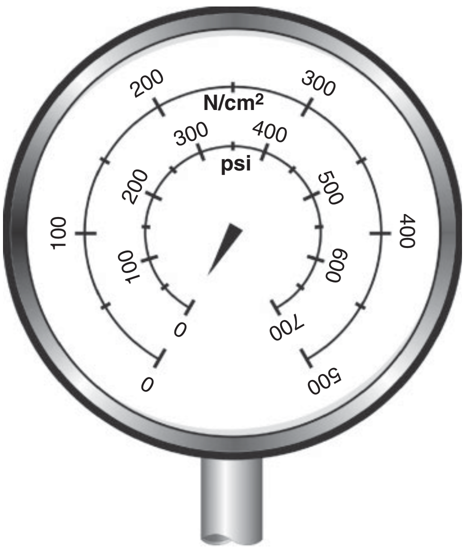

FIGURE 1-1. Pressure gauge with both psi and N/cm² units.

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2. *SPE Alphabetical List of Units*, SPE Publication, 2006.

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CHAPTER

Air and Gas Versus Mud

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This engineering practice monograph has been prepared for petroleum and related drilling and completion engineers and technicians who work in modern rotary drilling operations. This book derives and illustrates engineering calculation techniques associated with air and gas drilling technology. This book has been written in consistent units to ease application in either USCS or SI. Also, field unit equation use has been minimized in the text. Chapter 1 and Appendix A give definitions of important units and constants and useful conversions for both USCS and SI.

Air and gas drilling technology is the utilization of compressed air or other gases as a rotary drilling circulating fluid to carry the rock cuttings to the surface that are generated at the bottom of the well by the advance of the drill bit. The compressed air or other gas (e.g., nitrogen or natural gas) can be used also or can be injected into the well with incompressible fluids such as fresh water, formation water, formation oil, or drilling mud. There are three distinct operational applications for this technology: air or gas drilling operations (using only compressed air or other gas as the circulating fluid), aerated drilling operations (using compressed air or other gas mixed with an incompressible fluid), and stable foam drilling operations (using compressed air or other gas with an incompressible fluid to create a continuous foam circulating fluid).

In the past, air and gas drilling methods have been a small segment of the petroleum deposit recovery drilling industry. Currently, air and gas drilling methods that utilize compressed air (or other gases), aerated fluids, or foam fluids comprise about 20 to 30% of all operations. There are two separate and unique reasons for utilizing air and gas drilling methods in modern oil and gas deposit recovery operations. These are:

Performance Drilling: Drilling formations above a potential producing formation to generally take advantage of increased rates of penetration of these drilling methods.

Underbalanced Drilling: Drilling of potential producing formations using annulus bottom hole pressures that are below the formation pore pressure. This reduces or eliminates formation damage that could affect follow-on production.

In general, the use of air and gas drilling methods is confined to mature sedimentary basins within mature geologic provinces.

Pneumatic conveying represents the first use of moving air to transport entrained solids in the flowing stream of air. This airstream was created by steam-powered fans that were the direct outgrowth of the industrial revolution of the early sixteenth century. Pneumatic conveying was accomplished on an industrial scale by the late 1860s [1]. The need for higher pressure flows of air and other gases led to the first reliable industrial air compressors (stationary) in the late 1870s [2]. Here again, these early compressors were steam powered. After the development of the internal combustion engines, portable reciprocating and rotary compressors were possible. These portable compressors were first utilized in the late 1880s by an innovative mining industry to drill in mines using pneumatic-actuated hammers for in mine wall boreholes and shaft pilot boreholes [2].

2.1 ROTARY DRILLING

Rotary drilling is a method used to drill deep boreholes in rock formations of the Earth's crust. This method is comparatively new, having been first developed by a French civil engineer, Rudolf Leschot, in 1863 [3]. The method was initially used to drill water wells using fresh water as the circulation fluid. Today, this method is the only rock drilling technique used to drill deep boreholes (greater than 3000 ft, or *900 m*). It is not known when air compressors were first used for the drilling of water wells, but it is known that deep petroleum and natural gas wells were drilled utilizing portable air compressors in the 1920s [4]. Pipeline gas was used to drill a natural gas well in Texas in 1935 using reverse circulation techniques [5].

Today, rotary drilling is used to drill a variety of boreholes. Most water wells and environmental monitoring wells drilled into bedrock are constructed using rotary drilling. In the mining industry, rotary drilling is used to drill ore body test boreholes and pilot boreholes for guiding larger shaft borings. Rotary drilling techniques are used to drill boreholes for water, oil, gas, and other fluid pipelines that need to pass under rivers, highways, and other natural and man-made obstructions. Most recently, rotary drilling is being used to drill boreholes for fiber optics and other telecommunication lines in obstacle-ridden areas such as cites and industrial sites. The most sophisticated application for rotary drilling is the drilling of deep boreholes for the recovery of natural resources such as crude oil, natural gas, and geothermal steam and water. Drilling boreholes for fluid resource recovery usually requires boreholes drilled to depths of 3,000 ft (*900 m*) to as great as 20,000 ft (*6000 m*).

Rotary drilling is highly versatile. The rotary drilling applications given previously require the drilling of igneous, metamorphic, and sedimentary rock. However, the deep drilling of boreholes for the recovery of crude oil and natural gas is carried out almost exclusively in sedimentary rock. Boreholes for the recovery of geothermal steam and water are constructed in all three rock types. The rotary drilling method requires the use of a rock cutting or crushing drill bit. Figure 2-1 shows a tungsten carbide insert tricone roller cone bit. This type of drill bit uses more of a crushing action to advance the bit in the rock (see Chapter 4 for more details). These bits are used primarily to drill medium hard sedimentary rock.

To advance the drill bit in rock requires the application of an axial force on the bit (to push the bit into the rock face), torque on the bit (to rotate the bit against the resistance of the rock face), and circulating fluid to clear the rock cuttings away from the bit as the bit generates more cuttings with its advance (see Figure 2-2). If the axial force is missing and the other two processes are operating, then the bit will not advance. Likewise, if torque is not present and the other two processes are operating, then again the bit will not advance. However, if circulation is not present and the other two processes are present, the drill string will likely be damaged. This short discussion emphasizes the critical nature of the circulating system.

FIGURE 2-1. Tungsten carbide insert 7 7/8 inch (*200.1 mm*) tricone roller cutter bit IADC Code 627 (courtesy of Hughes Christensen Incorporated).

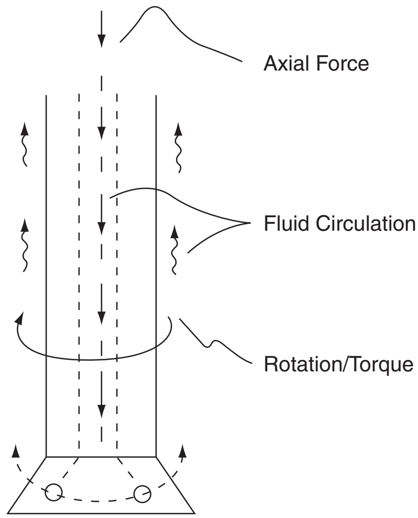

FIGURE 2-2. The three necessary components for rotary drilling.

Rotary drilling is carried out with a variety of drilling rigs. These can be small "single" rigs or larger "double" and "triple" rigs. Today, most of the drilling rigs based on land are mobile units with folding masts. A single drilling rig has a vertical space in its mast for only one joint of drill pipe. A double drilling rig has a vertical space in its mast for two joints of drill pipe and a triple drilling rig space for three joints. Table 2-1 gives API length ranges for drill collars and drill pipe [6].

Figure 2-3 shows a typical single drilling rig. Such small drilling rigs are highly mobile and are used principally to drill shallow (less than 3000 ft, or *900 m* in depth), such as coal-bed methane wells and geothermal hot water-producing boreholes. These single rigs are usually self-propelled. The self-propelled drilling rig shown in Figure 2-3 is a Gardner Denver SD 55. This particular rig uses a range 2 drill pipe.

Single rigs can be fitted with either an onboard air compressor or an onboard mud pump. Some of these rigs can accommodate both subsystems. These rigs have

Table 2-1. API Length Ranges for Drill Collars and Drill Pipe

Range	Minimum Length	Maximum Length
1	18 ft (*5.5 m*)	22 ft (*6.7 m*)
2	27 ft (*8.7 m*)	30 ft (*9.1 m*)
3	38 ft (*11.6 m*)	45 ft (*13.7 m*)

FIGURE 2-3. Typical self-propelled single drilling rig (courtesy of George E. Failing Company).

either a dedicated prime mover on the rig deck or a power take-off system that allows utilization of the truck motor as the prime mover for the drilling rig equipment (when the truck is stationary). Small drilling rigs can provide axial force to push the drill bit into the rock face through the drill string (via a chain or cable actuated pull-down system, or a hydraulic pull-down system). A pull-down system transfers a portion of the weight of the rig to the top of the drill string and then to the drill bit. The torque and rotation at the top of the drill string are also often provided by a hydraulic top-head drive (similar to power swivel systems used on larger drilling rigs), which is moved up and down the mast (on a track) by the chain, cable, or hydraulic drive pull-down system. However, some of these rigs retain the traditional rotary table. Many of these small single drilling rigs are capable of drilling with their masts at angles as high as 45° to the vertical. The prime mover for these rigs is usually fueled by either propane or diesel.

The schematic layout in Figure 2-4 shows a typical self-propelled double drilling rig. This example rig is fitted with a mud pump for circulating drilling mud. A vehicle motor is used to propel the rig over the road.

The same motor is used in a power take-off mode to provide power to the rotary table, draw works, and mud pump. For this rig, this power take-off motor operates a hydraulic pump that provides fluid to hydraulic motors to operate the

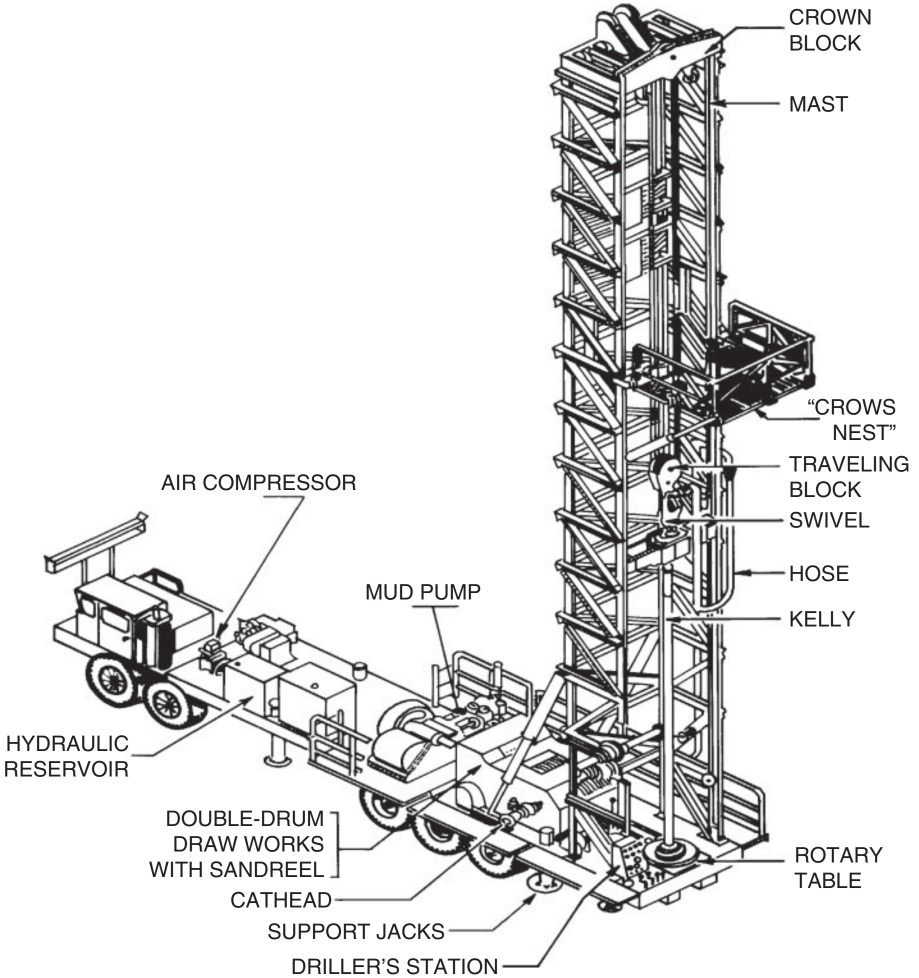

FIGURE 2-4. Typical self-propelled double drilling rig schematic layout.

rotary table, draw works, and mud pump. The "crows nest" on the mast indicates that the rig is capable of drilling with a stand of two joints of drill pipe. This drilling rig utilizes a rotary table and a kelly to provide torque to the top of the drill string. The axial force on the bit is provided by the weight of the drill collars at the bottom of the drill string (there is no chain pull-down capability for this drilling rig). This example schematic shows a rig with onboard equipment that can provide only drilling mud or treated water as a circulation fluid. The small air compressor at the front of the rig deck operates the pneumatic controls of the rig. However, this rig can easily be fitted for air and gas drilling operations. This type of drilling rig (already fitted with a mud pump) would require an auxiliary hookup to an external air compressor(s) to carry out an air drilling operation. The compressor system and its associated equipment for air drilling operations are usually provided by a subcontractor specializing in these operations.

Figure 2-5 shows a new type of triple drilling rig for land operations. This rig is fitted with a power swivel instead of a rotary table. These new Flex Rigs must be assembled at the drilling location.

In addition to having the most modern drilling equipment (automatic pipe loader, single console operation, etc.), the design uniqueness of the Flex Rig

FIGURE 2-5. Helmerick and Payne Flex Rig 3 (courtesy of Helmerick and Payne Incorporated).

concept allows rapid rig-up and rig-down, which minimizes nondrilling time at the location. These rigs have been developed by Helmerick and Payne Incorporated, an international drilling contractor serving both on-land and off-shore drilling operations. These rigs are available in depth capabilities up to 18 000 ft (*5500 m*).

2.2 CIRCULATION SYSTEMS

Two types of circulation techniques can be used for either a mud drilling system or an air or gas drilling system. These are direct (conventional) circulation and reverse circulation.

2.2.1 Direct Circulation

Figure 2-6 shows a schematic of a rotary drilling, direct circulation mud system that would be used on a typical double (and triple) drilling rig. Direct circulation requires that the drilling mud (or treated water) flows from the slush pump

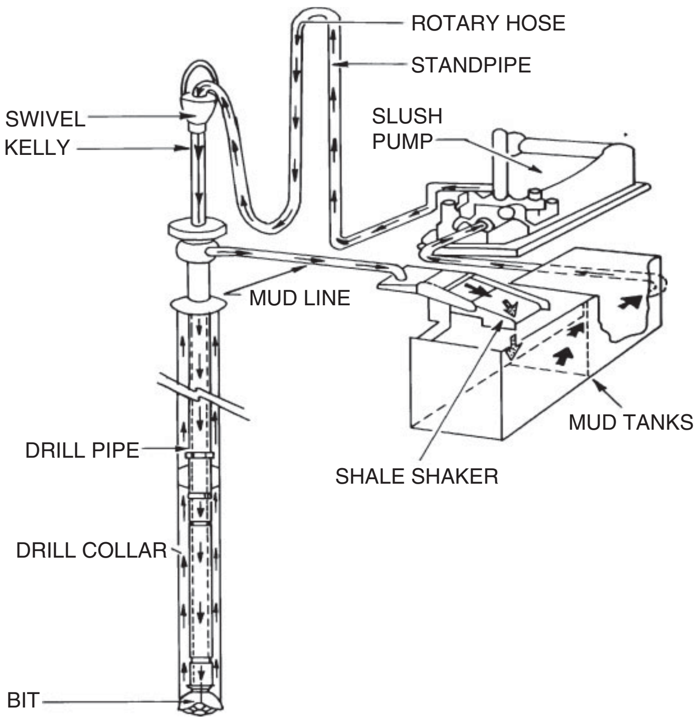

FIGURE 2-6. Direct circulation mud system.

(or mud pump), through the standpipe on the mast, through the rotary hose, through the swivel and down the inside of the kelly, down the inside of the drill pipe and drill collars, and through the drill bit (at the bottom of the borehole) into the annulus space between the outside of the drill string and the inside of the borehole.

The drilling mud entrains the rock bit cuttings at the bottom of the annulus and then flows with the cuttings up the annulus to the surface where the cuttings are removed from the drilling mud by the shale shaker and the drilling mud is returned to the mud tanks (where the slush pump suction side picks up the drilling mud and recirculates the mud back into the well). The slush pumps used on double (and triple) drilling rigs are positive displacement piston-type pumps.

For single drilling rigs, the drilling fluid is often treated fresh water in the mud tank. A heavy-duty hose is run from the suction side of the onboard mud pump (see Figure 2-4) to the mud tank. The drilling water is pumped from the tank, through the pump, through an onboard pipe system, through the rotary hose, through the hydraulic top-head drive, down the inside of the drill pipe, and through the drill bit to the bottom of the well. The drilling water then entrains the rock cuttings from the advance of the bit and carries the cuttings to the surface via the annulus between the outside of the drill pipe and the inside of the borehole. At the surface, the drilling fluid (water) from the annulus with entrained cuttings is returned to a mud pit where the rock cuttings are allowed to settle out to the bottom. The pumps on single drilling rigs are small positive displacement reciprocating piston types.

Figure 2-7 shows a detailed schematic of a direct circulation compressed air drilling system that would be used on a typical double or triple drilling rig.

Direct circulation requires that atmospheric air be compressed by the compressor and then forced through the standpipe on the mast, through the rotary hose, through the swivel and down the inside of the kelly, down the inside of the drill pipe and drill collars, and through the drill bit (at the bottom of the borehole) into the annulus space between the outside of the drill string and the inside of the borehole. The compressed air entrains the rock bit cuttings and then flows with the cuttings up the annulus to the surface where the compressed air and the entrained cuttings exit the circulation system via the blooey line. The compressed air and cuttings exit the blooey line into a large pit dug into the ground surface (burn pit). These pits are lined with an impermeable plastic liner.

If compressed natural gas is to be used as a drilling fluid, a gas pipeline is run from a main natural gas pipeline to the drilling rig. Often this line is fitted with a booster compressor. This allows the pipeline natural gas pressure to be increased (if higher pressure is needed) before the gas reaches the drilling rig standpipe.

2.2.2 Reverse Circulation

Rotary drilling reverse circulation (using either drilling mud and/or compressed air or gas) can be a useful alternative to direct circulation methods. The reverse

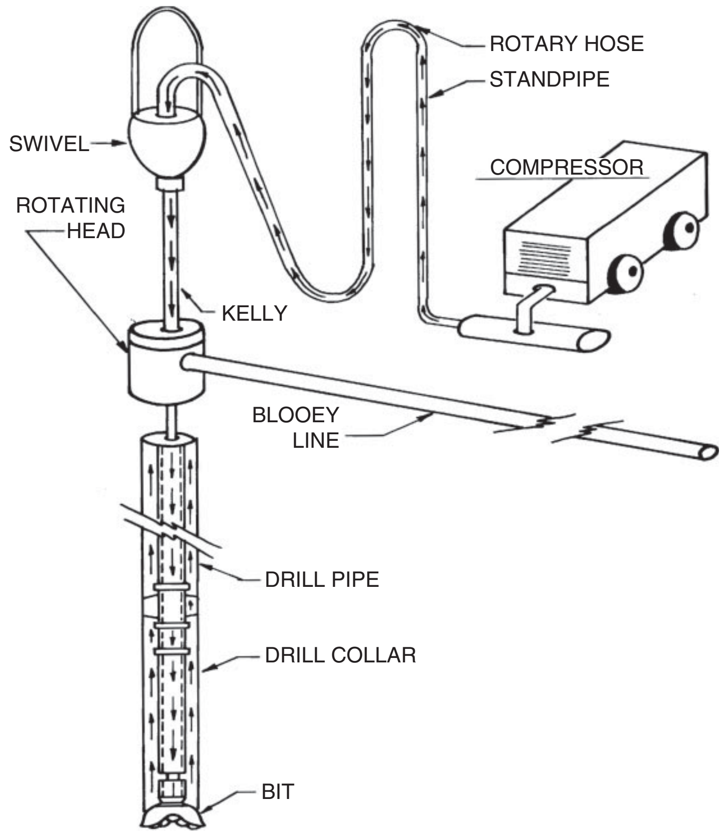

FIGURE 2-7. Direct circulation air system.

circulation technique is particularly useful for drilling relatively shallow large diameter boreholes (e.g., conductor and surface casing boreholes).

In a typical reverse circulation operation utilizing drilling mud, the drilling mud flows from the mud pump to the top of the annulus between the outside of the drill string and the inside the borehole, down the annulus space to the bottom of the borehole. At the bottom of the borehole the drilling mud entrains the rock bit cuttings and flows through the large center opening in the drill bit and then upward to the surface through the inside of the drill string. At the surface, the cuttings are removed from the drilling mud by the shale shaker and the drilling mud is returned to the mud tanks (where the pump suction side picks up the drilling mud and recirculates the mud back to the well).

Reverse circulation can also be carried out using air and gas drilling techniques. Figure 2-8 shows a typical application of reverse circulation using compressed air as the drilling fluid (or mist, unstable foam) [7]. This example is a

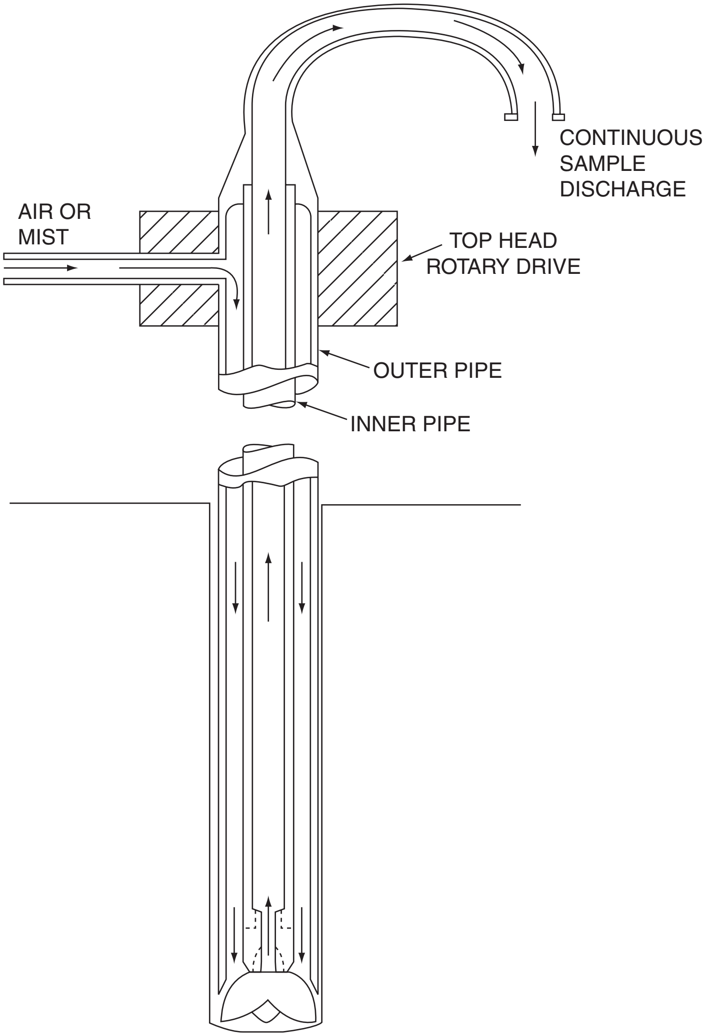

FIGURE 2-8. Dual tube (or dual drill pipe) closed reverse circulation operation.

dual tube (or dual drill pipe) closed reverse circulation system. The closed system is characterized by an annulus space bounded by the inside of the outer tube and the outside of the inner tube. This is a specialized type of reverse circulation and is usually limited to small single and double drilling rigs with top-head rotary drives (see Chapter 4 for drill pipe details).

Reverse circulation drilling operations require specially fabricated drill bits. Figure 2-9 shows a schematic of the interior flow channel of a tricone rotary drill

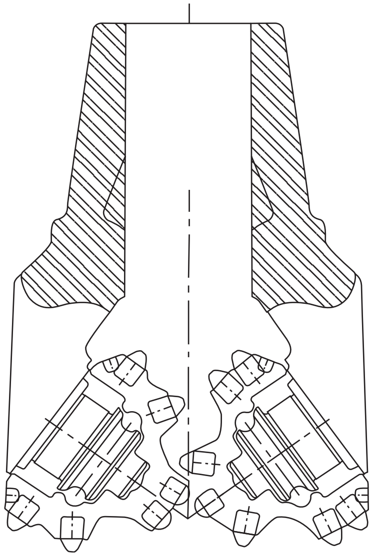

FIGURE 2-9. Schematic of the internal flow channel of a tricone roller cutter bit designed for reverse circulation operations (courtesy of Smith International Incorporated).

bit designed for reverse circulation. These drill bits utilize typical roller cutter cones exactly like those used in direct circulation drill bits (see Figure 2-1). These bits, however, have a large central channel opening that allows the circulation fluid flow with entrained rock cuttings to flow from the bottom of the borehole to the inside of the drill string and then to the surface.

Most tricone drill bits with a diameter of 5 3/4 inches (*146 mm*) or less are designed with the central flow channel as shown in Figure 2-9. Figure 2-1 showed the typical tricone drill bit for direct circulation operations. These direct circulation drill bits usually have three orifices that can be fitted with nozzles. Tricone roller cutter drill bits for reverse circulation operations are available in diameters from 4 1/2 inches (*114 mm*) to 31 inches (*787 mm*). The larger diameter bits for reverse circulation operations are usually custom designed and fabricated. Dual wall pipe reverse circulation operations require special skirted drill bits (see Chapter 4 for details). These skirted drill bits are specifically designed for the particular drilling operation. These specialized drill bits are usually manufactured by mining equipment companies.

2.3 COMPARISON OF MUD AND AIR DRILLING

The direct circulation model is used to make some important comparisons between mud drilling and air and gas drilling operations.

2.3.1 Advantages and Disadvantages

There are some very basic advantages and disadvantages to mud drilling and air drilling operations. The earliest recognized advantage of air and gas drilling technology was the increase in drilling penetration rate relative to mud drilling operations. Figure 2-10 shows a schematic of the various drilling fluids (the top four comprise air and gas drilling technology) and how these drilling fluids affect the drilling penetration rate. The drilling fluids in Figure 2-10 are arranged with the lightest at the top of the list and the heaviest at the bottom. The lighter the fluid column in the annulus (with entrained rock cuttings), the lower the confining pressure on the rock bit cutting face. This lower confining pressure allows the rock cuttings from the rock bit to be removed more easily from the cutting face (see Chapter 4 for more details).

Figure 2-11 shows a schematic of the various drilling fluids and their respective potential for avoiding formation damage. Formation damage is an important issue in

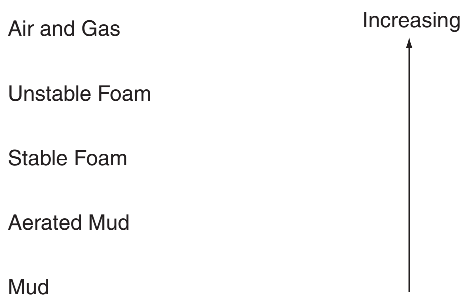

FIGURE 2-10. Improved penetration rate.

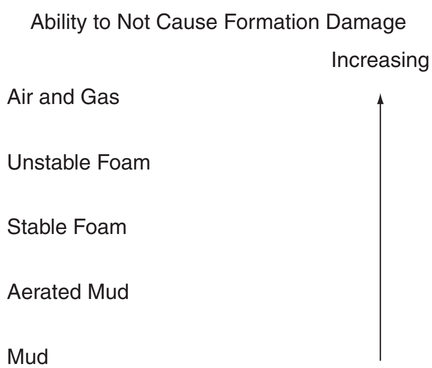

FIGURE 2-11. Formation damage avoidance.

fluid resource recovery (e.g., oil and natural gas, and geothermal fluids). The lighter the fluid column in the annulus (with entrained rock cuttings), the lower the potential for formation damage (arrow points upward to increasing avoidance of formation damage). Formation damage occurs when the fluid column pressure at the bottom of the borehole is higher than the pore pressure of the resource fluid (oil, gas, or water) in the potential producing rock formations. This higher bottom hole pressure forces the drilling fluid (with entrained rock cutting fines) into the exposed fractures and pore passages in the producing rock formations. These fines plug these features in the immediate region around the borehole. This damage is often called a "skin effect." This skin effect damage restricts later formation fluid flows to the borehole, thus reducing the productivity of the well.

Figure 2-12 shows a schematic of the various drilling fluids and their respective potential for avoiding loss of circulation. Loss of circulation occurs when drilling with drilling muds or treated water through rock formations that have fractures or large interconnected pores or vugs. If these features are sufficiently large and are not already filled with formation fluids, then as drilling progresses the drilling fluid that had been flowing to the surface in the annulus can be diverted into these fractures or pore structures. This diversion can result in no drilling fluid (with entrained rock cuttings) returning to the surface. The rock cuttings are left in the borehole and consolidate around the lower portion of the drill string and the drill bit. If this situation is not identified quickly, the drill string will begin to torque up in the borehole and mechanical damage to the drill string will occur. Such damage can sever the drill string and result in a fishing job to retrieve the portion of the drill string remaining in the borehole.

For deep oil and natural gas recovery wells, loss of circulation can result in even more catastrophic situations. If drilling fluids are lost to thief formations, the fluid column in the annulus can be reduced, resulting in a lower bottom hole pressure. This low bottom hole pressure can cause a high pressure oil and/or natural gas "kick" or geothermal fluid "kick" (a slug of formation fluid) to enter the

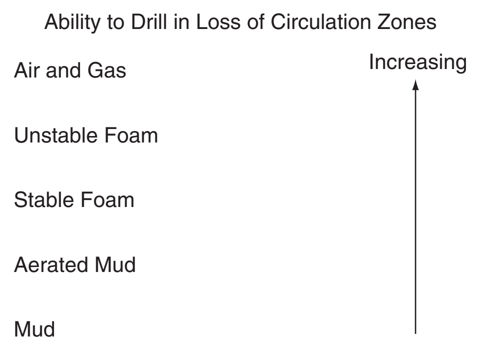

FIGURE 2-12. Loss of circulation avoidance.

annulus. Such kicks must be immediately and carefully circulated out of the annulus (to the surface), as an uncontrolled blowout of the well could occur. Here again heavier drilling fluids are generally more prone to loss of circulation (arrow points upward to increasing loss of circulation avoidance).

Figure 2-13 shows a schematic of the various drilling fluids and their respective potential for use in geologic provinces with high pore pressures. High pore pressures are encountered in oil, natural gas, and geothermal drilling operations. New discoveries of oil, natural gas, or geothermal fluid deposits are usually highly pressured. In order to safely drill boreholes to these deposits, heavily weighted drilling muds are utilized. The heavy fluid column in the annulus provides the high bottom hole pressure needed to balance (or overbalance) the high pore pressure of the deposit.

Figure 2-13 also shows that the heavier the drilling fluid column in the annulus, the more useful the drilling fluid is for controlling high pore pressure (the arrow points downward to increasing capability to control high pore pressure). There are limits to how heavy a drilling mud can be. As discussed earlier, too heavy a drilling mud results in overbalanced drilling, which can result in formation damage. However, there is a greater risk to overbalanced drilling. If the drilling mud is too heavy, the rock formations in the open hole section can fracture. These fractures will result in a loss of the circulating mud in the annulus that could result in a blowout.

In the past decade it has been observed that drilling with a circulation fluid that has a bottom hole pressure slightly below that of the pore pressure of the fluid deposit gives near optimum results. This type of drilling is denoted as underbalanced drilling. Underbalanced drilling allows the formation to produce fluid as the drilling progresses. This lowers or eliminates the risk of formation damage and eliminates the possibility of formation fracture and loss of circulation. In general, if the pore pressure of a deposit is high, an engineered adjustment to the

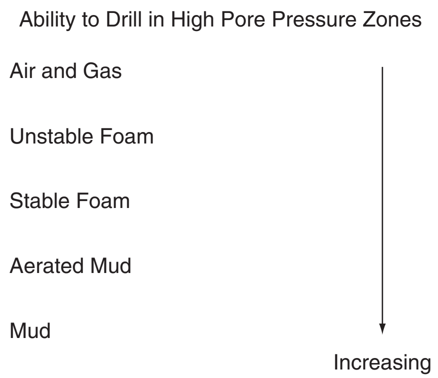

FIGURE 2-13. Controlling high pore pressure.

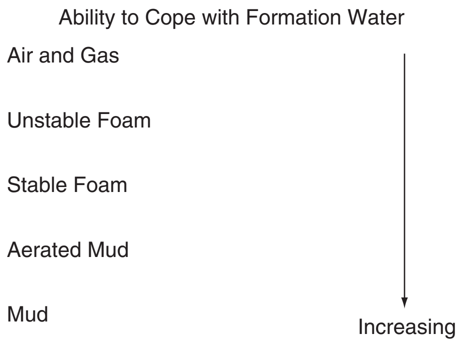

FIGURE 2-14. Control of the inflow of formation water.

drilling mud weight (with additives) can yield the appropriate drilling fluid to assure underbalanced drilling. However, if the pore pressure is not unusually high, then air and gas drilling techniques are required to lighten the drilling fluid column in the annulus.

Figure 2-14 shows a schematic of the various drilling fluids and their respective potential for keeping formation water out of the drilled borehole. Formation water is often encountered when drilling to a subsurface target depth.

This water can be in fractures and pore structures of the rock formations above the target depth. If drilling mud is used as the circulating fluid, the hydrostatic pressure of the mud column in the annulus is designed to be sufficient to keep formation water from flowing out of the exposed rock formations in the borehole. Lighter drilling fluids, such as compressed air or other gases and foam, have lower bottom hole pressure and, therefore, lower the pressure on any formation water in the exposed fractures or pore structures in the drilled rock formations.

Figure 2-14 shows that the heavier drilling fluids have a greater ability to cope with formation water flow into the borehole (the arrow points downward to increasing control of formation water). This has always been a distinct advantage for deep targets in young immature sedimentary rock formations. In some drilling situations, a foam drilling fluid system can be designed to take on formation water when the foam system has extra foamer added to it. Aerated drilling fluids are capable of handling influxes of formation fluids. However, all these air and gas based drilling fluids are restricted to older mature sedimentary geologic provinces.

2.3.2 Flow Characteristics

A comparison is made of the flow characteristics of mud drilling and air drilling in a deep well example. A schematic of this example well is shown in Figure 2-15.

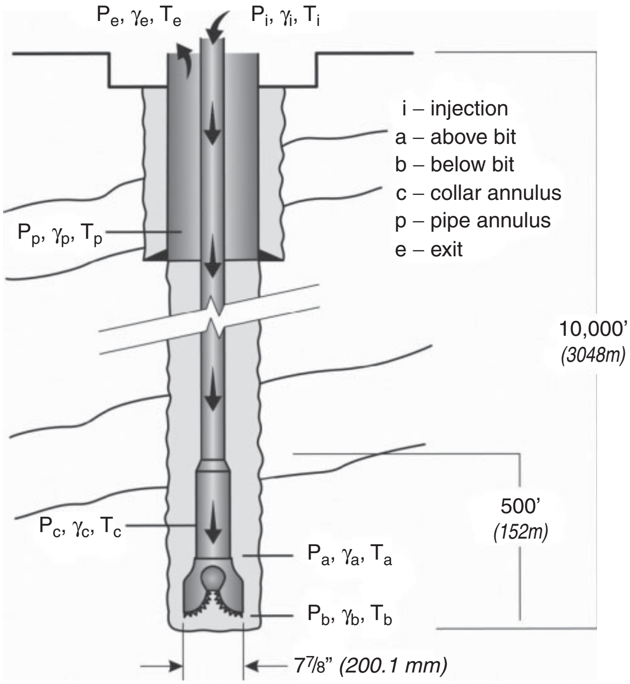

FIGURE 2-15. Comparison example well and drill string.

The well is cased from the surface to 7000 ft (*2133 m*) with API 8 5/8-in (*219 mm*) diameter, 32.00 lb/ft (*14.60 kg/m*) nominal casing. The well has been drilled out of the casing shoe with a 7 7/8-in (*200 mm*)-diameter drill bit. The comparison is made for drilling at 10,000 ft (*3048 m*). The drill string in the example well is made up of (bottom to top) a 7 7/8-in (*200 mm*)-diameter drill bit, ~500 ft (*152 m*) of 6 1/4-in (*159 mm*) outside diameter by 2 13/16-in (*71 mm*) inside diameter drill collars, and ~9500 ft (*2895 m*) of API 4 1/2-in (*114 mm*) diameter, 16.60-lb/ft (*7.52 kg/m*) nominal, IEU-S135, NC 46, drill pipe.

The mud drilling hydraulics calculations are carried out assuming that the drilling mud weight (i.e., specific weight) is 10 lb/gal (*density of 1201 kg/m*^{3} *or 1.2 kg/liter*), the Bingham mud yield is 10 lb/100 ft^2 (*48 N/10 m*^{2}), and the plastic viscosity is 30 centipose. The drill bit is assumed to have three 12/32-in (*9.5 mm*)-diameter nozzles with a drilling mud circulation flow rate of 200 gal/min (*757 liters/min*). Figure 2-16 shows plots of the pressures in the incompressible drilling mud as a function of depth and shows a plot of the pressures inside the drill string. The injection pressure is approximately 1072 psig (*739 N/cm*^{2} *gauge*) and 5877 psig (*4049 N/cm*^{2} *gauge*) at the bottom of the inside of the drill string just above the bit nozzles. Also shown is a plot of the pressure in the annulus. The

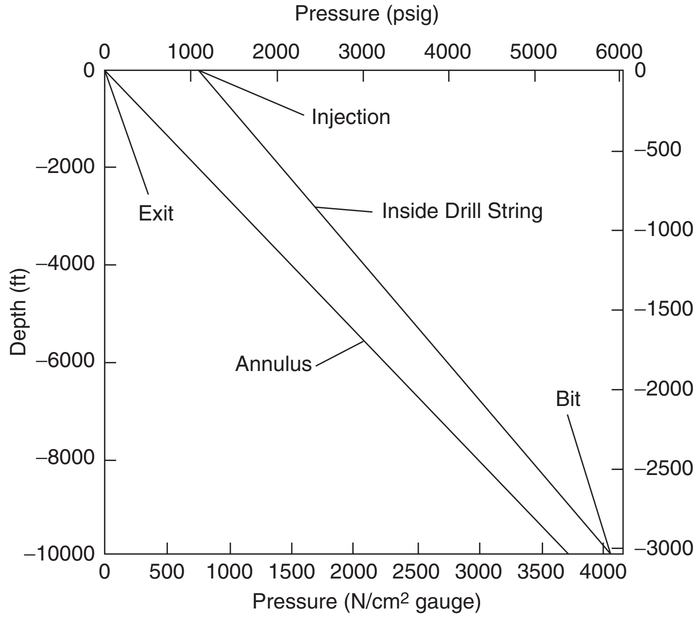

FIGURE 2-16. Mud drilling pressure versus depth.

pressure is approximately 5401 psig (*3721 N/cm^2 gauge*) at the bottom of the annulus just below the bit nozzles and 0 psig (*0 N/cm^2 gauge*) at the top of the annulus at the surface.

The pressures in Figure 2-16 reflect the hydrostatic weight of the column of drilling mud and the resistance to fluid flow from the inside and outside surfaces of the drill string, the surfaces of the borehole wall, and the bit nozzle orifices.

This resistance to flow is the result of friction losses of energy in the fluid. The total losses due to friction are the sum of all the aforementioned losses. This mud drilling example shows a total loss through the system of approximately 1071 psi (*739 N/cm^2*). This includes the approximate 476 psi (*328 N/cm^2*) loss through the drill bit. Smaller diameter nozzles would yield higher losses across the drill bit and higher injection pressures at the surface.

The air drilling calculations are carried out assuming the drilling operation is at sea level. There are two compressors capable of 1200 scfm (*566.3 standard liters/sec*) each, so the total volumetric flow rate to the drill string is 2400 scfm (*1133 standard liters/sec*). The drill bit is assumed to have three open orifices at 0.75 in (*19 mm*) diameter. Figure 2-17 shows the plots of the pressures in the compressible air as a function of depth and shows a plot of the pressure inside the drill string. The pressure is approximately 245 psia (*169 N/cm^2 absolute*) at injection and 201 psia (*139 N/cm^2 absolute*) at the bottom of the inside