NIPER/BDM-0200

TOPICAL REPORT

INDUSTRY STATE-OF-THE-ART IN UNDERBALANCED DRILLING

by

Tao Zhu, Len Volk, and Herbert Carroll

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Work Performed Under Contract No.
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ABSTRACT

This report discusses the current state of drilling underbalanced by industry. Underbalanced drilling is generally achieved by introducing a gas into the drilling fluid. This can range from air drilling (no liquid) to aerated fluids containing only a small percent of gas. Much of the paper is dedicated to discussing the advantages and limitations. The principle advantages are increased productivity through minimizing formation damage and increased penetration rate. The main disadvantage is the absence of adequate modeling to achieve and maintain the underbalanced condition. This report also discusses the various methods of achieving an underbalanced condition.

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ADVANCEMENTS IN UNDERBALANCED DRILLING

1.0 INTRODUCTION

Drilling a well requires fluid (or mud) to maintain wellbore hydraulic pressure and remove the cuttings generated. In conventional drilling, pressure in the wellbore is greater than the local formation pressure. This condition is referred to as drilling overbalanced. In order to control fluid loss and fines invasion, a low-permeability filter cake is intentionally deposited on the wellbore wall; however, effective and continuous control of fluid leak-off and solids migration through the filter cake deposition is virtually impossible. The act of forming a filter cake requires some fluid loss, and periodic breakdown in the filter cake is inevitable because of the action of the drillpipe and fluid turbulence. In most cases, the overbalanced pressure, combined with complex mud systems and drill cuttings, can damage formations significantly and severely reduce their permeability. Formation damage is of particular concern in horizontal and extended-reach well drilling because boreholes are exposed to drilling and completion fluids for significant longer periods of time, and open hole completions are common for most horizontal and extended-reach wells, resulting in greater depth of fluid invasion. As a result, natural gas and oil in many oil fields cannot be adequately recovered because of formation damage caused by drilling fluid invasion. Therefore, prevention of formation damage becomes a major concern.

Recently, underbalanced drilling (i.e., drilling with wellbore pressure less than the local formation pressure) has been used to minimize invasive formation damage in both horizontal and vertical wells. When properly designed, underbalanced drilling can prevent formation damage, increasing productivity and lowering completion costs. In most applications of underbalanced drilling, depleted formation pressure requires that the drilling fluid be lightened by entraining a gas phase. Typical underbalanced drilling operations are designed to produce fluid pressure just below static formation pressure. In these cases, the underbalanced drilling is designed to maintain wellbore pressure slightly below formation pore pressure. During underbalanced drilling, operators find that it is very difficult to create and maintain an underbalanced condition at all times throughout the wellbore. An accurate predictive model is the key requirement for any underbalanced drilling operation (Collins 1994; Shale 1995; Teel 1995). The resulting two-phase flow conditions must be analyzed and quantified.

In underbalanced horizontal drilling, the most important issue is cuttings transport from the bit to the surface. Underbalanced drilling usually involves two-phase flow. Two-phase flow in a horizontal or deviated section of the well will result in phase stratification and slug flow, which then will result in significant liquid slip, with higher gas velocities than liquid velocities. Cuttings may accumulate in either a stationary or moving bed, risking stuck pipe, lost circulation, high torque and drag forces, and poor cement jobs (Adewumi et al. 1993). The severity of such problems depends on cuttings' size, density, and shape, the drilling fluid rheology and velocity, and the hole/pipe configuration (Adewumi et al. 1993). The specific mechanism depends on the wellbore angle. For high angles, where a stationary cuttings bed can form, rolling is a main transport mechanism. For intermediate angles, where a moving bed can form, lifting is the dominate transport mechanism (Clark and Bickham 1994). Therefore, modeling is a key requirement to ensure that the cuttings transport capability is sufficient for horizontal and deviated hole cleaning. Accurate predictions to quantify the liquid phase velocity is required in order to ensure that minimum velocity requirements are met (Guo et al. 1993).

In some cases, foam may be selected as the drilling fluid. With foam, a number of key factors must be simulated and analyzed. For example, cuttings transport capabilities are most sensitive to foam quality, particularly in deviated or horizontal holes (Kitsios et al. 1994). Because foam moves in plug flow, re-entrainment of drill cuttings is not as easy as in turbulent flow. Therefore, foam qualities and flow velocity must be accurately predicted to improve cutting transport. In addition, produced formation fluids, such as hydrocarbons, will alter the quality of foam and may destabilize it. In order to preserve foam quality and stability, balanced or slightly overbalanced conditions should be employed. To accomplish these conditions, accurate modeling is critical to ensure that there is no significant fluid losses.

Most researchers realize that the models should consider a range of parameters, such as fluid rheology, annular configuration, well depth, hole orientation, and bottomhole conditions (Adewumi et al. 1993; Guo et al. 1993; Clark et al. 1994). In addition, several design options must be evaluated and optimized prior to implementation. This modeling process is the key to ensuring that underbalanced conditions are achieved and that operational costs are minimized.

2.0 APPLICATIONS AND ADVANTAGES OF UNDERBALANCED DRILLING

In many domestic oil fields, formation pressures are partially or completely depleted, so that natural gas and oil cannot be recovered due to formation damage resulting from drilling fluid invasion. Recently, underbalanced drilling has been used as a technique to minimize invasive formation damage in both horizontal and vertical wells.

The severity of the drilling fluid damage depends on the quantity and properties of the invading fluid and the formation. There are two options for minimizing formation damage during drilling. One option is to control the properties of the drilling fluid by using nondamaging fluids. Developing and using nondamaging drilling fluids are expensive. The other option is to minimize the amount of drilling fluid invading the formation. Underbalanced drilling is designed to do this.

In addition to prevent formation damage, underbalanced operations are also a practical and effective way to prevent lost circulation and differential sticking. Since the pressure in the formation is actually higher than the pressure in the wellbore, stuck pipe incidents caused by differential pressure are eliminated.

Underbalanced drilling also increases the rate of penetration. Reduced hydrostatic pressure at the bottom of the borehole reduces the effective stress acting on the element of rock being subjected to the bit cutter. Reducing the effective stress results in a decrease in the apparent rock strength, which reduces the resistance of the rock to the action of the bit cutter, increasing the penetration rate. An increase in rate of 2–4 times is not unusual, and sometimes by a factor of 10. Increased penetration rate helps lower the total well cost by cutting drilling time, and it contributes to reduced formation damage by shortening the time that the formation is exposed to drilling fluid.

Because formation fluids are produced during underbalanced drilling, drilling this way reduces mud requirements, thereby reducing mud cost and environmental impact. In addition, reduced formation damage can minimize the need for expensive stimulation and lower the ultimate completion costs. Production rate increases of seven times that anticipated have been reported when underbalanced conditions were achieved (Gregory 1995).

In summary, underbalanced drilling offers several advantages over conventional drilling or overbalanced drilling:

- Minimized formation damage
- Increased rates of penetration
- Improved bit performance
- Elimination of differentially pressure stuck pipe
- Lower mud costs
- Reduced lost circulation risk
- Reduced environmental impact.

Coiled tubing and slimhole drilling techniques are particularly applicable with underbalanced conditions.

2.1 MINIMIZING FORMATION DAMAGE

The primary reason to perform underbalanced drilling is to minimize formation damage. Underbalanced drilling has been used successfully to control or minimize formation damage in vertical and horizontal wells. In conventional drilling, the hydrostatic pressure in the wellbore is greater than the pressure in the formation, and this pressure difference can result in a reduction in formation permeability and well productivity. Bennion et al. (1994) summarized the types of formation damage that can occur:

- Fluid-fluid incompatibilities
- Rock-fluid incompatibilities
- Mud solids invasion
- Phase trapping/blocking
- Chemical adsorption and wettability modification
- Formation fines migration

During drilling and well completion, invaded mud filtrate may react with formation fluids (such as oil or brine) to form scales, insoluble precipitates, asphaltic sludges, or stable emulsions. Invading mud filtrate may also react with minerals in the rock such as smectite, illite, chlorite, and kaolinite clays, resulting in swelling or deflocculating which may severely reduce near-wellbore permeability. In some cases, drilling fluid additives can cause a number of undesirable phenomena, such as permeability reduction by polymer adsorption or wettability alteration by surfactant adsorption.

Invasion of solids and migration of formation fines are two other mechanisms of formation damage during drilling. The invasion of solids contained in the drilling fluid (i.e., weighting material or artificial bridging agents) or formation solids (microfines) generated by the milling action of the drill bit can cause a severe reduction of permeability in some situations. The actual internal movement of formation fines or loosely attached in-situ formation particles can be of concern in certain reservoirs where high, uncontrolled fluid loss takes place in permeable formations.

Recently, underbalanced drilling has been employed to prevent formation damage in the Austin Chalk in central Louisiana (Joseph 1995A). In 1994, OXY USA successfully drilled underbalanced a 19,000 ft horizontal well in central Louisiana. The initial productivity of the well was about 12.9 mmcfd of gas, 3 mcfd of condensate, and 7 mcfd of water on a 1/2-in. choke, with 4,124 psi flowing tubing pressure (Joseph 1995B). Several other wells were drilled in this area using conventional techniques in the late 1970s and early 1980s, and none of these were commercial successes because they suffered significant formation damage through the loss of thousands of barrels of heavy mud to the Austin Chalk (Joseph 1995A).

In recent years, there has been an increasing interest in combining underbalanced drilling techniques with multilateral drilling to develop new and existing reservoirs. Petro-Hunt Corporation, employing underbalanced drilling techniques to prevent formation damage, drilled an opposed, dual horizontal well in the Austin Chalk formation of South Texas (Cooney et al. 1991). From both drilling efficiency and production standpoints, the well was very successful. In an initial test, the well produced 0.46 bbl/day/ft of exposed formation as compared to the 24 well average of 0.30 bbl/day/ft, for a 53% increase in productivity.

Recently, Lunan (1995) reported that a closed loop underbalanced drilling system had been used to drill over 200 wells in the Western Canadian Basin to minimize the potential for lost circulation and formation damage. For example, underbalanced drilling in a pressure depleted reservoir (the Elkton Shunda Pool) resulted in an oil recovery increase of from 0.4 m^3/hr (or 60 bbl/day) to 3.3 m^3/hr (or 498 bbl/day) (Lunan, 1995)

2.2 MINIMIZING LOST CIRCULATION

When lost circulation occurs, the drilling mud does not return to the surface and the cuttings generated by the bit cannot be removed from the wellbore. Lost circulation is the most troublesome and costly problem during drilling due to the need to replace lost drilling fluid and to the time lost to fix the problem.

Lost circulation can occur while drilling into highly permeable unconsolidated formation such as loose sand and gravel. It can also occur if the formation being drilled is naturally fractured or cavernous. In mature reservoirs, drilling fluid may be readily lost to depleted formations since the hydrostatic pressure in the wellbore is greater than the formation pressure. Circulation can also be lost due to induced fracturing if the wellbore pressure is greater than the least principal stress.

Operators used underbalanced drilling for control of lost circulation as early as the 1950s. El Paso Natural Gas Company (Wilson 1951) employed natural gas as drilling fluid in the Blanco area of the San Juan Basin in northwestern New Mexico to drill intervals with a high risk of lost circulation. El Paso Natural Gas reported that underbalanced drilling with gas increased the penetration rate from an average of 0.5 ft/minute to 1 ft/minute. In addition, the bit life was increased from 80 ft to more than 300 ft of hole.

In 1991, Marathon Oil Company (Clayton et al. 1991) employed aerated drilling techniques to drill a horizontal well in Jackson County, Michigan. The formations in this area are vuggy and fractured. Drilling with conventional mud would result in partial or total loss of fluid returns. By using aerated drilling fluid, the well was drilled successfully. Also, underbalanced drilling was effectively used to drill more than 1,800 horizontal wells in the Austin Chalk formation in Texas (Joseph 1995A). These horizontal wells were drilled perpendicular to the natural fractures.

The Divide Creek Unit 29 in Mesa County, Colorado (Carden 1993) is another example of drilling underbalanced to control lost circulation. This well ran into severe lost circulation problems starting at 1480 ft. As drilling progressed, the lost circulation problems increased. By 1686 ft, the operator had decided to start drilling with air and mist, solving the lost circulation problem. At 2300 ft, the well encountered a large water influx. To reduce the volume of water entering the wellbore, an aerated mud system was run. Lost circulation was again encountered between 2948 and 3235 ft. The interval was drilled with no surface returns even though only air was being pumped down the well. Circulation was regained below 3235 ft, and drilling continued with aerated fluid.

As the previous examples show, underbalanced drilling can be used to minimize lost circulation problems. The savings in time more than offsets the additional cost of the underbalanced drilling equipment because the drilling process was not interrupted to combat lost circulation problems.

2.3 REDUCING DRILLING COSTS

The primary reduction in drilling costs are associated with increased penetration rate, which yields savings in rig time, overhead costs, and supervision costs. The degree to which the drilling rate is reduced is a function of the differential pressure between the mud and the formation. This differential pressure reduces drilling rates by inhibiting dislodgment of the chip and by acting as a confining pressure and strengthening the rock. In addition, savings results from reduced incidence of lost circulation and reduced mud use. The following equation is commonly used to calculate the per foot drilling cost:

$$Cost\ /\ foot = \frac{B + C_r(t + T)}{F}$$

where: B is the bit costs ($), C_r is the rig operating costs ($/hr), t is the rotating time (hr), T is the round trip time (hr) and F is the footage per bit (ft).

Bowen and Parkhouse (1978) reported a savings of $1 million while drilling 4,100 ft of 26-in.-diameter hole in Iran. Parkhouse and Teesdale (1984) also reported that three major oil companies (Union Texas, Total, and AGIP) used underbalanced drilling technique to overcome lost circulation problems and reduce drilling costs in Tunisia. They claimed that the savings resulted from the use of less lost circulation materials and other drilling fluid additives reduced the number of bits, resulting in less drilling time and related costs.

In the early 1980s, Exxon drilled three wells in the Paradox Basin, Utah, by using underbalanced drilling techniques (Sheffield 1985). The primary purpose of using underbalanced drilling was to avoid the risk of lost circulation and sloughing in water sensitive shales. The first well, using dry air, mist, and foam, drilled to 11,725 ft, the second to 9,826 ft, and the third to 5,470 ft. An estimated 53 operating days and $1 million were saved for the first well drilled, $624,000 for the second well, and $368,000 for the third well.

Reduced drilling costs by using underbalanced drilling was also recognized from different regions in the United States. Carden (1993) reported that the increase in penetration rate by using underbalanced drilling was as high as 10 times compared with conventional mud system. For example, in the Federal G-2-2-1045 well (Uinta-Piceace-Eagle Basin), bit number 5 drilled at a penetration rate of 34.3 ft/hr while drilling underbalanced. The well was mudded up for the next bit run, and the penetration rate decreased to 3.5 ft/hr. In Wyoming (Carden 1993), the penetration rate for the Reservoir Creek Unit I-34 well was 5.95 ft/hr with mud and 31.31 ft/hr underbalanced—over 5 times faster. Carden (1993) also reported that higher penetration rates were achieved for underbalanced drilling in the Paradox Basin, Uinta Basin, and Piceane Creek Basin. In the 6 Andy's Mesa well (Paradox Basin) the penetration rate with underbalanced drilling was 23.57 ft/hr vs. 10.42 ft/hr for mud. To illustrate the economics of overbalanced vs. underbalanced drilling, a 3,600 ft well drilled underbalanced would require approximately six drilling days at a rate of 25.65 ft/hr. This same well drilled using mud would take 22 days at a penetration rate of 6.65 ft/hr. Typically, the average daily operating cost drilling underbalanced is around $9,000/day, whereas the cost is $6,500/day for conventional mud drilling (Carden 1993). Therefore, the cost of drilling the same well underbalanced (aerated mud) vs. overbalanced (conventional mud system) is $54,000 and $143,000, respectively.

2.4 UNDERBALANCED DRILLING COMBINED WITH COILED TUBING AND SLIMHOLE TECHNOLOGY

Recently, underbalanced drilling combined with coiled tubing slimhole technology has attracted considerable attention. Coiled tubing is smooth and continuous. The use of a continuous string eliminates the drillstring connections, which reduces the risk of blowout during underbalanced drilling operations and results in time saving. Continuous drilling strings significantly improve safety for rig crews because of the reduced risk of blowout and the reduced interaction between people and equipment. In addition, coiled tubing permits drilling and tripping continuously while circulating drilling fluid. This results in a significant improvement in underbalanced performance because it becomes possible to achieve 100% underbalanced conditions.

In September 1992, Pan Canadian Petroleum (PCP) completed deepening a sour gas well underbalanced in Alberta (Lloyd and Scherschel 1993). The primary target of this well was a gas zone at about 6800 ft. The formation immediately above the producing zone is a high pressure formation with a pressure gradient of about 0.53 psi/ft (or pressure of 3,545 psi). Information from an offset well indicated that the producing formation pressure was only about 2,500 psi. Conventional drilling techniques would result in a 1,200 psi overbalanced pressure. Previously drilled offset wells had proven that drilling with conventional technique would result in severe formation damage due to formation sensitivity and problems associated with phase trapping of mud filtrate and completion fluids. Therefore, underbalanced drilling techniques were employed so as to allow the sensitive formation to flow during drilling operation. No drilling fluid would invade the formation and little damage would be sustained. Coiled tubing drilling was selected because it met the principle objective (Lloyd and Scherschel 1993). In addition, coiled tubing offered the benefit of short trip times and a circulating system that could be totally enclosed to contain H_2S. PCP claimed that the drilling operation was viewed as a success. However, the well experienced overbalanced conditions during drilling and logging.

PCP realized that detailed knowledge of formations and accurate modeling of downhole conditions are critical to a successfully drilling a well (Lloyd and Scherschel 1993).

More recently, a slimhole horizontal well in Alaska (Slimhole Special Edition 1994) was drilled using underbalanced techniques combined with coiled tubing drilling, resulting in significant increase in oil production. The well was drilled to a depth of 8,900 ft using conventional drilling, then extended horizontally with coiled tubing and underbalanced drilling. The bottomhole assembly (BHA) used to drill the horizontal drainhole included a 3-in. bit, a 2-in. steerable motor, a Slim1 MWD system with gamma-ray capability mounted in 3-in. nonmagnetic collars, and an orientation tool for steering. Real-time data supplied by the Slim1 MWD system enabled the driller to closely follow the planned trajectory. It is reported that formation damage was minimized by drilling underbalanced. As a result, production from the well was 3,800 BOPD, 2,600 BOPD more than the 1,200 BOPD the operator estimated would have been produced if the horizontal drainhole had been conventionally drilled and completed (Slimhole Special Edition 1994).

3.0 LIMITATIONS OF UNDERBALANCED DRILLING

There are several concerns with drilling underbalanced. It may increase the risk of blowout, fire, explosion, and loss of control. In this section, the limitations of underbalanced drilling will be discussed.

3.1 WELLBORE INSTABILITY

In the oil industry, wellbore instability is a problem in all drilling operations whether the well is drilled underbalanced or overbalanced. However, hole instability is of particular concern for underbalanced drilling because of the increased chance of sloughing. Sloughing is the process by which pieces or the wellbore wall break off and fall into the hole. Sloughing can be caused by several reasons: abnormal formation pressure, tectonic stresses, and the presence of water sensitive clays (Grace and Carden 1995). When the well is drilled through a highly pressured or stressed formation with underbalanced methods, the pressure or stress near the wellbore changes. This change causes wellbore instability.

A formation may also slough if it is water sensitive. This is especially true for shale sections. A water sensitive formation is one that contains hydratable clays that react with water. All shales have an affinity for water. However, certain types of clay will absorb water causing them to swell or enlarge. When the bonding forces are less than the hydrating forces, the clay expands, and the only place for it to expand is into the wellbore. This can cause pieces of the formation to slough off the wellbore wall.

Sloughing can cause wellbore cleaning problems and stuck drill pipe. For example, a horizontal well was to be drilled in Florence Field, Colorado (Carden 1993). The well was sidetracked from an existing well at a depth of 2660 ft. Air drilling was continued with only minor hole cleaning problems to 5149 ft. At 5149 ft, the well entered an oil zone. Oil can cause the pipe to become stuck or cause a downhole fire when drilling with dry air. Therefore, the operator started mist drilling. In less than one day, the water sensitive shales in the hole started to slough and the drill string became stuck. The well was eventually abandoned because the string could not be recovered.

3.2 SAFETY CONSIDERATIONS

Safety is always an issue for any drilling operation. In an underbalanced drilling operation, the pressure in the annulus is less than the formation pore pressure and the blowout preventer on the well head is always under pressure. This may not be a problem in normal situations. However, if the hole enters a high pressure zone, particularly a high pressure gas zone, the annular pressure may increase rapidly and exceed the maximum allowable blowout preventer pressure. Currently, blowout preventers are limited to 1500 psi flowing pressure and 2000 psi static pressure. Underbalanced drilling, therefore, is limited to drilling into formations with low pore pressure. This is of particular concern for oil or gas reservoirs containing H_2S gas. In addition, the well may be producing formation fluids, including hydrocarbons. Therefore, there is always the potential for a blowout, explosion or fire around a drilling rig.

Underbalanced drilling experiences have proven that very few accidents (such as explosions or fires) have been caused by gas or oil flowing from a well (Carden 1993). However releases may occur during tripping because the rotating head is removed so that the drilling tools can be pulled from the well.

3.3 DIRECTIONAL CONTROL CONCERNS

One of the major concerns for underbalanced drilling (specifically for air, mist, foam, and aerated fluid drillings) is directional drilling. Most tools used in directional drilling were developed for liquid mud drilling and have been adapted to underbalanced drilling. The success of underbalance directional drilling has had mixed results.

In horizontal drilling, positive displacement motors (PDM) are used for building and drilling horizontal section. Because air is compressible, the flow rate changes with pressure. In underbalanced drilling, the flow rate is much higher than in conventional drilling because of the cutting transport requirements. However, the higher fluid flow rate exceeds the optimum flow rate for the drill motors, often causing premature failure. To prevent motor problems caused by excessive flow rate, some of the fluid must bypass the motor. This can be done by placing a jet sub above the motor (Carden 1991).

Another problem is the measurement-while-drilling (MWD) tools. Currently, no MWD system is available that will work consistently in underbalanced drilling environments. MWD equipment requires mud (liquid) to transmit information as pressure pulses from the bottom hole assembly to the surface. Because most underbalanced drilling fluids are compressible, they cannot be pulsed effectively. Therefore, conventional mud-pulse MWD technology does not work in an underbalanced environment. Recently, an electromagnetic measurement-while-drilling (EMWD) system has been developed to operate by using radio waves to send information to the surface; it will work in compressible fluids. However, the results from EMWD are not consistent, and the system is subject to failure because drilling conditions are rougher than in mud-filled holes. For example, Conoco (Carden 1993) used EMWD to drill the North Tisdale 87 well in Johnson County, Wyoming, and was able to drill the entire build and horizontal section without failure. Unfortunately, the Southwest Rangely Federal 84-1-2 well (Carden 1993) in Rio Blanco County, Colorado, attempted horizontal section using air with EMWD tools was not successful. The operator drilled the build section with mud using EMWD without a problem, but failed almost immediately on switching to air drilling. The well was nonproductive, so the operator drilled a sidetrack to the original horizontal well. Again the EMWD was used and failed.

3.4 HOLE CLEANING PROBLEMS

Cuttings removal is another problem when drilling underbalanced, particularly for horizontal holes. Hole cleaning is particularly difficult when the hole inclination is above 50° because cuttings no longer fall to the bottom, but instead lie on the side of the hole. The volume of drilling fluid needed to clean a horizontal section is much greater than for a vertical section. The cleaning problems are even more pronounced when using mist or dry air (which have less fluid viscosity) as a drilling fluid.

4.0 UNDERBALANCED DRILLING TECHNIQUES

Underbalanced drilling is obtained when the effective downhole circulating pressure of drilling fluid is less than the formation pore pressure. In many cases, particularly in pressure depleted formations, it is necessary to artificially reduce the mud density and hydrostatic pressure in order to generate underbalanced conditions. There are four types of underbalanced drilling techniques, each with its specific purpose and application:

- Air drilling
- Mist drilling
- Foam drilling
- Aerated fluid drilling

By choosing the right technique, the operator can successfully perform underbalanced drilling for a variety of specialized drilling applications.

4.1 AIR DRILLING

Air drilling uses air (or gas) as circulating fluid. One major purpose of this circulating air is to transport cuttings from the bottom of the hole to the surface. Air drilling requires adequate quantities of circulating air to effectively clean the hole. Low rates will result in cutting accumulation in the wellbore, particularly when drilling horizontally. On the other hand, circulating more air than is required causes unnecessary pressure loss, consumes more compressor power, and increases operational costs. In addition, the maximum penetration rate is achieved at the minimum bottom hole pressure. Higher air velocities also accelerate equipment erosion. It has been demonstrated that the key to achieving the optimal drilling rate with air drilling is to use an optimum air volumetric flow rate.

There are several advantages of using air as a circulating fluid. First, the rate of penetration is significantly greater compared to mud. Rates five to six times that of conventional drilling are common (Adervumi and Tian 1993). This results in decreased tripping and less drilling time. In a deep well, these decreased trip times will result in substantial cost savings. Second, air drilling causes less formation damage, which is particularly important for water-sensitive formations and for achieving maximum productivity. In addition, air drilling has less impact on the environment since it does not contain any chemical additives.

Other advantages of air drilling include:

- Greater footage per bit than any drilling fluid
- Better cement jobs (no mud filtercake)
- Better completion
- Improved production (no fluid or mud fines invasion).

There are several limitations to using air drilling techniques. As mentioned previously, because air does not contain any additives to stabilize the wellbore or build a filtercake, air drilling is not suitable for unstable formations. In addition, air drilling is usually used for formations that are either dry or have small water influx. When drilling in water-saturated formations, cuttings will be mixed with water to form mud. This naturally formed mud can cause serious problems. It can wet any water-sensitive shales, causing wellbore instabilities. When cuttings fill the annulus, a mud ring may form, sticking the drill pipe and stopping air flow. Therefore, in wet formations, other underbalanced drilling techniques should be used.

4.2 MIST DRILLING

In mist drilling, air is the continuous phase and an aqueous phase appears as discontinuous droplets. Mist drilling is normally used to drill wet formations, but the amount of water influx can not be so high as to cause hole cleaning problems. During mist drilling, a small quantity of water containing a foaming agent is injected with the gas (air, nitrogen, natural gas, carbon dioxide, or inert gases from engine exhaust) at the surface. The foaming agent reduces the interfacial tension between the water and cuttings allowing small water/cuttings droplets to be dispersed as a fine mist in the returning fluid stream, eliminating the formation of mud rings and bit balling.

There are disadvantages in using mist drilling. The proper amount of water and soap mixture must be injected into wellbore to achieve a normal operating condition. However, determining the proper combination of water and soap is very difficult. It is a function of the type and volume of influx water. Many formation brines are effective defoamers, and produced oil requires special types of soap to create a foam. Mist drilling requires a greater gas volume than air drilling, which results in about twice the pressure. If insufficient foam agent or air is used, the injection pressure will increase significantly.

In either air or mist drilling, if air (containing oxygen) is used as the injecting gas and hydrocarbons are encountered, downhole fires may occur. A downhole fire occurs when wet gas or gas and oil are present with air at sufficient pressure and temperature to reach ignition conditions. The explosion of a downhole fire is a very impressive occurrence. Typically, the drill collars and bits melt, making fishing operation impossible (Shale 1995). However, downhole fires can be prevented by introducing measured amounts of cold water to prevent ignition temperature from being reached. It also can be prevented by using carbon dioxide, nitrogen, or exhaust gas instead of air.

4.3 FOAM DRILLING

In foam drilling, the drilling fluid is a foam consisting of water, surfactant, and gas (such as air) with water being the continuous phase and gas being discontinuous bubbles. Foam can be generated at the injection point by pumping the water/surfactant solution through a venturi tube into the air/gas system (Shale 1995), by passing the various fluid components through a porous medium (Raza 1965), or in a coiled tubing generator (Okpobiri and Ikoku 1986).

Foam quality is defined as the ratio of gas volume to the total volume. Low-quality foams are referred to as wet foams; high-quality foams are called dry foams. The preferred range of gas-to-liquid is 3–50 ft^3 of gas/gal. of water (Shale 1995). The foam quality will change with depth or pressure and can be adjusted according to downhole requirements. Other chemical additives, such as bentonite and polymers, can be added to the foam to modify its properties.

There are several advantages to using a foam instead of an air or mist system. First, foams offers superior fluid and cutting-carrying capabilities, and thus require significantly lower annular velocities. In foam drilling, it is not uncommon for the annular velocity to be as low as 50 ft/minute (Dupont 1984). Lower annular velocity can reduce hole erosion. In certain formations where underbalanced drilling is needed due to low fracture gradients, erosion from the high annular velocities of air or mist systems could prohibit its use.

Other advantages of foam drilling are superior cuttings transport and the elimination of downhole fires. Because foam has a high viscosity, it can transport large cuttings to the surface. The potential for a downhole explosion or fire is virtually eliminated since foams are air-internal systems. Furthermore, foam drilling reduces or eliminates mud buildup in the annulus. Foam is also better able to remove produced water. Operations using foam are capable of effectively removing as much as 500 bbl/hr of downhole fluid influx (Shale 1995). All of these advantages make foam systems one of the most versatile of all underbalanced drilling systems.

However, the solids-carrying capacity of any foam is a function of its velocity, density, and rheological properties. A foams density is dependent on the air/liquid volume ratio, which is dependent on the depth, or pressure. Therefore, a clear understanding of the rheology and multiphase fluid flow mechanisms of foam systems are of primary importance in predicting the various operating parameters needed for foam drilling.

Another important consideration for foam drilling is foam stability. Formation brines and hydrocarbons are usually effective defoaming agents. Foam quality will be degraded by high formation-fluid production. To ensure that little or no formation fluid is produced, wells are ideally drilled slightly overbalanced. However it is very difficult to maintain this slightly overbalanced or balanced conditions. Accurate predictive model can help operators to obtain and maintain these conditions.

4.4 AERATED MUD DRILLING

Aerated mud is used when water production is too great to be removed by mist or foam techniques. An aerated-mud system is an air-internal fluid created by injecting air or an inert gas (such as nitrogen or carbon dioxide) into a conventional mud. The system combines the advantages associated with conventional mud drilling and air drilling techniques. The aerated mud can be effectively used for drilling low pressure reservoirs, natural fractured reservoirs, or water producing reservoirs without lost circulation. An aerated-mud system also can have chemical additives to reduce viscosity and frictional force, eliminate or reduce fluid loss, and create good corrosion control characteristics. There are three different techniques used for gas injection: two-phase, parasite, and microannulus.

4.4.1 Two-Phase Injection

In two-phase injection, both mud and gas phases are introduced upstream of the standpipe, resulting in a co-mingled circulation system (shown in Figure 4–1). The most significant benefit is its applicability to both new wells and re-entries. Other benefits of this technique are no additional downhole equipment is needed, thus lowering the total operation costs, and gas consumption is lower compared to the parasite injection method (discussed in the following paragraph).

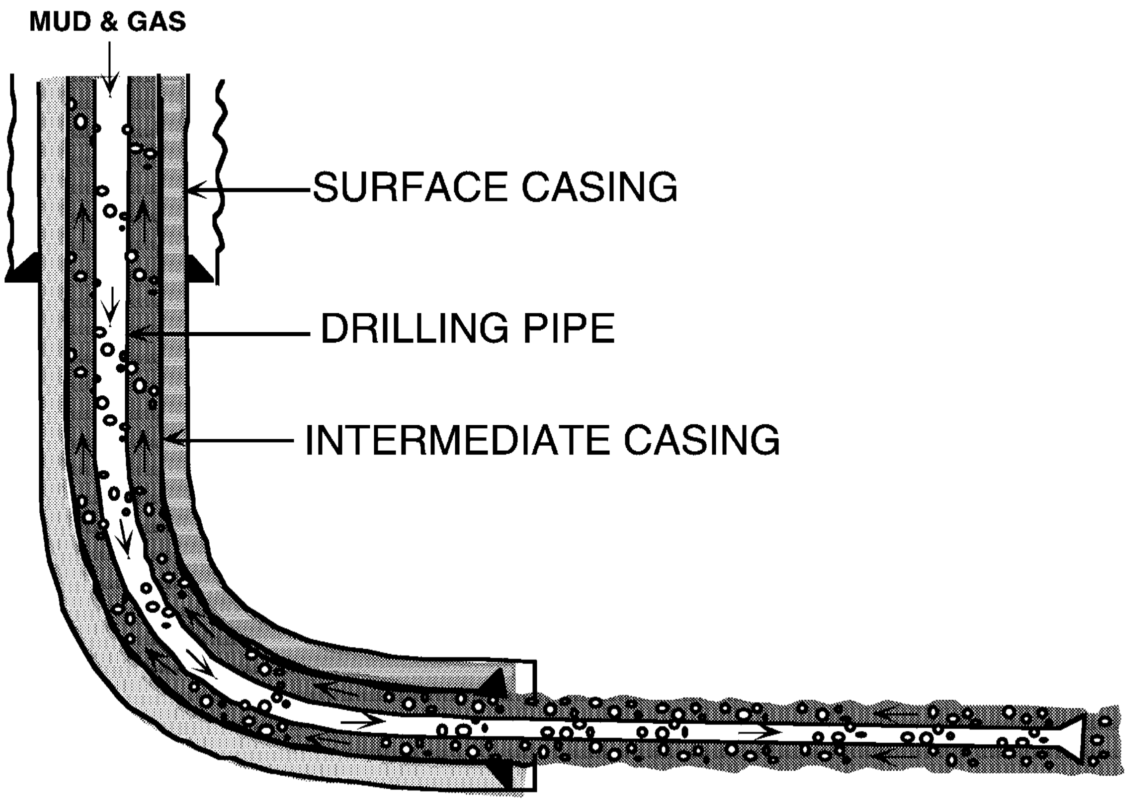

Figure 4–1 Two-Phase Injection Method for Underbalanced Drilling

There are a number of operational challenges in applying two-phase injection techniques. With a gas phase in the drillpipe, mud-pulse MWD becomes ineffective. In order to perform a mud-pulse MWD survey, gas injection must be temporarily shut down while continuing to pump mud until the drillpipe becomes filled by liquid. Changing the drill pipe fluid from two-phase to continuous liquid phase and back to two-phase can cause bottomhole pressures to fluctuate from underbalanced to overbalanced conditions, resulting in formation damage. Second, there is no tool face indication while drilling in an underbalanced condition. If tool face information is needed, the gas injection has to be shut off until liquid fills the entire drillpipe. Again, formation damage may occur.

4.4.2 Parasite Injection

In this method, an injection string introduces the gas at a fixed point (shown in Figure 4–2). Typically, this injection string is 1-in. coiled tubing which is run outside of the casing and cemented in place in the annulus during the primary cement job. The gas injection point is an injection sub which is usually installed at some point in the build section. To minimize the risk of damage to the parasite string, the injection sub is installed not lower than 45° in the build section. Non-aerated mud is injected downhole through the drillstring. At the same time, gas is introduced through the parasite string to the injection point and enters the annulus to co-mingle with the mud and then returns to surface. Gas injection is maintained at a rate to reduce the hydrostatic pressure in the vertical column sufficiently to ensure that the well is drilled in an underbalanced condition. There are several advantages of using a parasite injection system:

- Conventional mud-pulse MWD can be used because only a liquid phase is in the drillpipe.
- Gas injection is not dependent upon the drilling operation.
- Gas circulation may be continued during the operation of connecting the drillpipes, surveying trippings, or repairs to maintain the wellbore in an underbalanced condition.

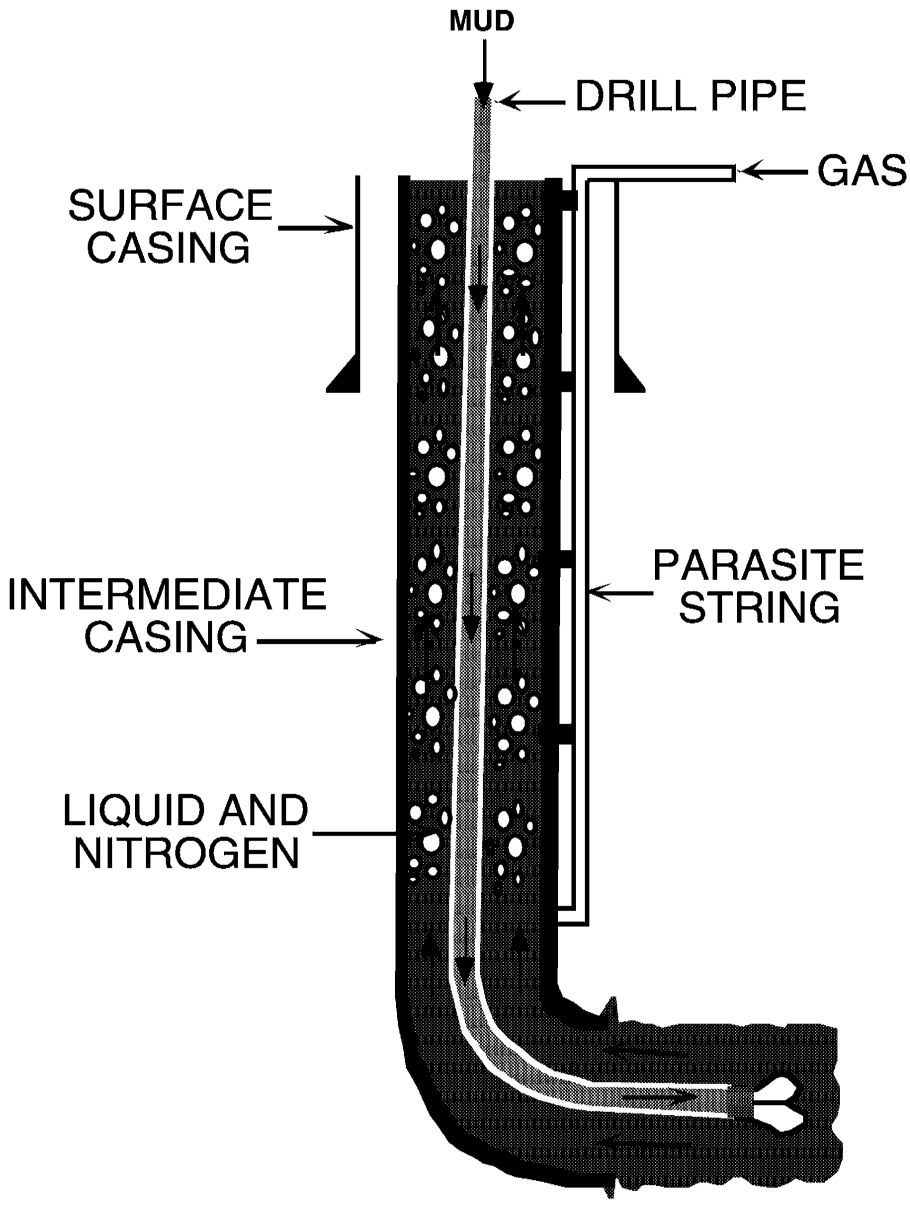

Figure 4–2 Parasite Injection Technique for Underbalanced Drilling

There are, however, many disadvantages in using parasite injection techniques:

- It cannot be used for re-entry wells because the gas injection string is run outside of the casing and cemented in place in the annulus during the primary cement job.
- Installation of a parasite string can be very costly. The drilling of an oversized hole, the extra cement and rig time, and the cost of the parasite string will significantly increase the total cost of the well.
- The fluid below the gas entry point can not be aerated so that the drilling fluid column weight may not be low enough to ensure the underbalanced conditions.
- The gas injection point is fixed.

More gas consumption is required when compared to two-phase injection for two primary reasons. First, the gas injection is installed at some point between the kick-off point and 45° in the build section, therefore the vertical height from the drill bit to the injection sub will experience full hydrostatic pressure from liquid-mud before a higher gas injection ratio is introduced to make up for this head difference. Second, and more significant, the throughput requirements of the positive displacement motor requires a specified flow rate for optimum torque performance and the circulation rate through the drillpipe must satisfy this specified flow rate (Falk and McDonald 1995). In parasite operations, the entire flow requirement of the positive displacement motor comes from liquid circulation, and yet the gas injection rates have to be high enough to produce the required hydrostatic pressure reduction. On the other hand, in two-phase injection operations, the required motor flow rates are satisfied by the mixture of mud and injected gas. As a result, the overall gas consumption for parasite injection operations will be greater than two-phase injection operations.

There is also a chance of damaging the parasite string during installation and of drilling fluid entering the parasite string due to a nonfunctioning check valve (Dareing and Kelsey 1981).

4.4.3 Microannulus Injection

The microannulus injection technique (shown in Figure 4–3) is similar to the parasite injection process. In this application, a concentric casing string is run between production casing and drill string. Gas is injected into the annulus between the permanent production casing string and temporary casing string, while mud is pumped downhole through the drillstring as in a conventional drilling operation. Mud and gas are mixed at the bottom of the temporary casing string and return to the surface through the annulus between the temporary casing string and drillstring. Based on the computer modeling results, gas injection rates are maintained to reduce the hydrostatic pressure sufficiently to ensure that the well is drilled in an underbalanced condition.

Microannulus injection techniques have advantages and disadvantages when compared to parasite injection operations. Advantages include

- Injection point can be as much as 60° into the build section (Falk and McDonald 1995),
- It can be applied to re-entry wells (for large production casing)
- The temporary casing string can be pulled out after drilling operations.

The disadvantages are

- Large production casing strings are required to accommodate the temporary concentric casing string.
- An additional packer is needed to avoid fluid flow back into the microannulus during drilling.

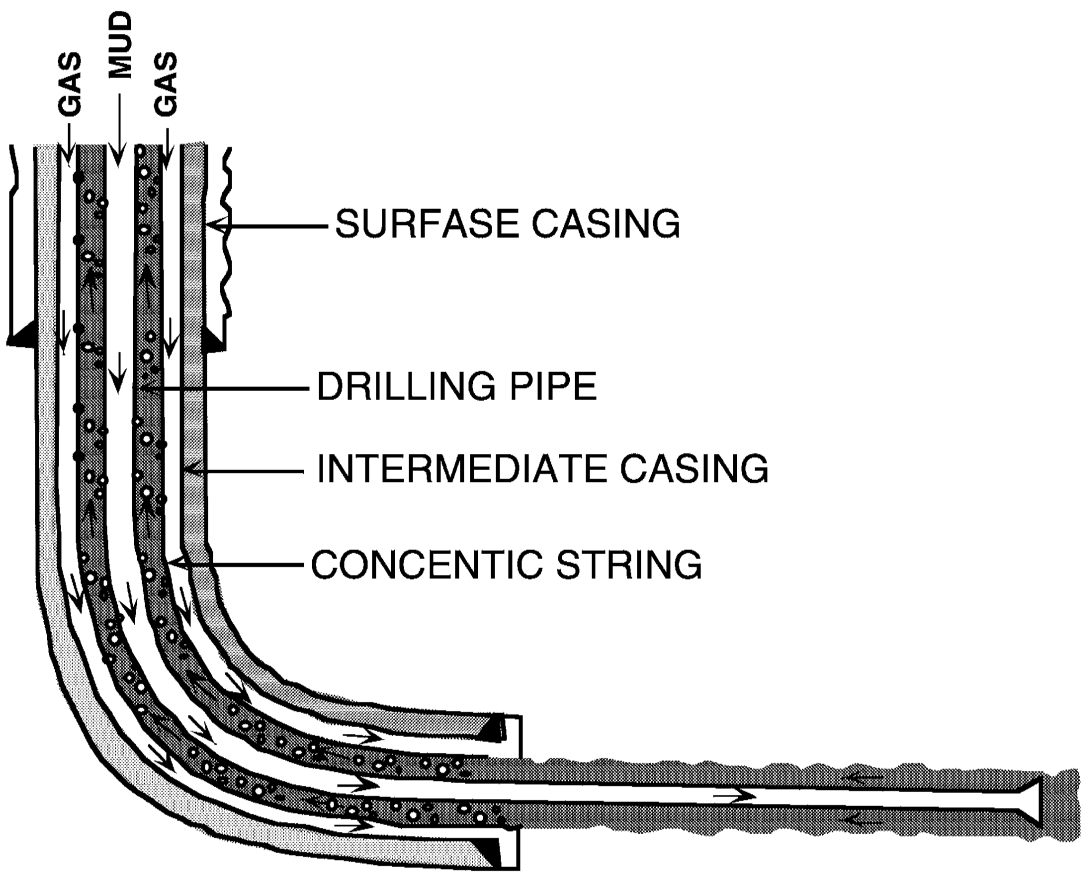

Figure 4–3 Microannulus Injection Technique for Drilling Underbalanced

5.0 UNDERBALANCED DRILLING MODELING

One major setback in the application of underbalanced drilling is the lack of understanding of wellbore hydraulics and the absence of an accurate predictive models to analyze and design drilling operations. As a consequence, the operating conditions for air drilling are not optimal, and therefore costs are higher in terms of rig time, personnel time, and equipment.

The predominant reason for drilling underbalanced is to reduce formation damage. However, the majority of underbalanced drilling fluid systems are not designed for low fluid loss. A stable filtercake is not developed during underbalanced drilling because of continual inflow from the formation. It may result in severe fluid loss to the formation if underbalanced conditions are not maintained 100% of the time. Therefore, post-drilling stimulation operations must be performed to repair the damage done to the pay zone due to an improperly designed underbalanced drilling operation.

To maintain underbalanced conditions 100% of the time, mathematical models for multiphase annular flow are essential. Models can be used to determine the optimum flow rate to predict downhole pressure losses, surface equipment needs, and the economics of the drilling prospect. However, only a few of these models exist, and they all make simplifying assumptions involving the effects of solids loading, solids size distribution, optimum annular air velocity, minimum annular pressure drop, particle-particle interaction forces, or the choking phenomenon. Consequently, a greater understanding of these effects is needed.

Angel (1957) was the first to use a mathematical model to predict the required volumetric flow rate and to incorporate the rate of penetration and the effects of the drill cuttings in the annulus for air drilling. Angel's equation relates the volumetric flow rate to the rate of penetration, hole depth, hole size, drillpipe size, and air specific gravity:

$$\frac{6.61S(T_s + Gh)Q^2}{\left(D_h^2 - D_p^2\right)^2 V_e^2} = \sqrt{(P^2 + bT_{av}^2)e^{2ah/T_{av}} - bT_{av}^2} \qquad (5\text{–}1)$$

where,

$$a = \frac{SQ + 28.8KD_h^2}{53.3Q}$$

$$b = \frac{1.625 \times 10^{-6} Q^2}{(D_h - D_p)^{1.333}(D_h^2 - D_p^2)^2}$$

D_h = hole diameter, ft

D_p = pipe diameter, ft

G = annular temperature gradient, $^\circ F / ft$

h = depth, ft

K = drilling rate, ft / hr

P = pressure, lb / ft^2

Q = circulation rate, Scf / min

S = specific gravity of gas

T_{av} = average temperature, $^\circ R$

V_e = velocity of standard density air, ft / min

However, the following simplifying assumptions were made in the development of this model.

- The air and the drill cuttings flowing in the annulus form a homogeneous mixture with the flow properties of an ideal gas. Thus, particle slip is ignored, and the calculated air volumetric flow rates should be regarded as minimum values.
- The application of the principle of hydraulic radius adequately modifies pipeline flow equations to account for annulus flow. The hydraulic radius theoretically converts flow in an irregularly shaped conduit into an equivalent circular pipeline. Flow calculations are then made with existing formulas designed for circular pipeline flow.
- The shape and size distribution of the drill cuttings do not affect the frictional forces developed in the annulus.
- Particle-particle interaction forces are neglected.

Angel (1957) also assumed a minimum velocity of 3000 ft/min to flow cuttings out of the well. However, some drilling operators believe a minimum annular velocity as high as 4000 ft/min is required in some situations (Supon and Adewumi 1991); others (Martin 1953) think a velocity of only 2,000 ft/min is adequate. Ikoku and Williams (1980) defined the minimum annular volumetric pressure drop as a design criterion for air drilling operations instead of the minimum annular volumetric velocity required to lift the cuttings out of the well.

$$p1 - p2 = \frac{\overline{\rho} g(h_2 - h_1)}{g_c} + \frac{u_p W_p}{g_c} + \Delta p_f \cdots \quad (5\text{–}2)$$

where,

$$\overline{\rho} = \rho_p(1-\varepsilon) + \rho_f\varepsilon = \rho_f\varepsilon\left(\frac{W_p u_f}{W_{up}} + 1\right)$$

$$W = u_f \rho_f \varepsilon \cdots$$

$$W_p = u_p \rho_p (1-\varepsilon) \cdots$$

h = height, ft

g = gravitational acceleration, ft / sec^2

g_c = conversion factor

p = pressure

u_f = gas velocity, ft / sec

up = particle velocity, ft / sec

Δp_f = frictional pressure drop, psi

W = mass velocity of gas, lb / in^2 / sec

W_p = mass velocity of solids, lb / in^2 / sec

ρ_f = density of gas, lb / cu ft

ρ_p = density of particle, lb / cu ft

$\overline{\rho}$ = density of gas - solid mixture, lb / cu ft

ε = void fraction, dimensionless

Ikoku and Williams (1980) also derived correlations for the terminal setting velocities of sandstone, limestone and shale particles, and the annular friction factor as follows:

for sandstones,

$$u_f = \left[\frac{2g}{C_D'}\frac{V_p}{A_p}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)^{1.03}\right]^{0.5} \cdots \qquad (5\text{–}3)$$

$$C_D' = 0.94$$

for shales,

$$u_f = \left[\frac{2g}{C_D'} \frac{V_p}{A_p} \left(\frac{\rho_p - \rho_f}{\rho_f} \right)^{0.315} \right]^{0.5} \cdots$$

$$\frac{D_{\min}}{D_{\max}} < 0.6 \qquad (5\text{–}4)$$

$$C_D' = 1.1$$

and for limestone,

$$u_f = \left[\frac{2g}{C_D'} \frac{V_p}{A_p} \left(\frac{\rho_p - \rho_f}{\rho_f} \right)^{1.05} \left(\frac{D_{\min}}{D_{\max}} \right)^{2.3} \right]^{0.5} \cdots$$

$$0.6 < \frac{D_{\min}}{D_{\max}} < 1.0 \qquad (5\text{–}5)$$

$$C_D' = 0.95$$

friction factor,

$$f_f = 0.0791 \left(\frac{\rho_f u_o D_t}{\mu_f} \right)^{-0.25} \text{ for } 3\times10^3 < R_e < 10^5 \qquad (5\text{–}6)$$

and,

$$f_f = 0.0008 + 0.0552 \left(\frac{\rho_f u_o D_t}{\mu_f} \right)^{-0.237} \text{ for } 10^5 < R_e < 10^8 \qquad (5\text{–}7)$$

where,

A_p = projected area of cutting in the direction of motion, square inch

C_D' = drag coefficient corrected for density and shape, dimensionless

$D_{\min}$ = minimum dimension of cuttings, inch

$D_{\max}$ = maximum dimension of cuttings, inch

D_t = pipe diameter, inch

f_f = fanning friction factor, dimensionless

R_e = Reynolds number

u_o = gas velocity at empty pipe basis, ft / sec

u_t = terminal velocity of falling particle, ft / sec

V_p = volume of cuttings, cu ft

Machado and Ikoku (1982) experimentally determined the cuttings friction factors. Their equations are as follows:

for sandstone,

$$f_s = 0.22056 \times 10^5 \left(\frac{g_c d_s}{{v_g}^2} \right)^{1.592} \left(\frac{w_s}{w_g} \right)^{0.975} \tag{5–8}$$

for limestone,

$$f_s = 0.47854 \times 10^5 \left(\frac{g_c d_s}{{v_g}^2} \right)^{1.751} \left(\frac{w_s}{w_g} \right)^{0.749} \tag{5–9}$$

for shale,

$$f_s = 0.110 \times 10^3 \left(\frac{g_c d_s}{{v_g}^2} \right)^{0.985} \left(\frac{w_s}{w_g} \right)^{1.088} \tag{5–10}$$

where,

d_s = diameter of solids, in. (cm)
f_f = Solid Fanning friction factor
g_c = gravitational constant
v_g = gas velocity, ft / min
w_{gt} = gas mass flow rate, lb / min
W_s = solid mass flow rate, lb / min

Wolcott and Sharma (1986) developed a computational model to calculate the annular pressure drop. Their model breaks up the annulus into a series of computational cells. The characteristics of each cell, including particle-size distribution, can differ. The total annular pressure drop is determined by summing the individual cell pressure drops.

Little work has been done recently in the area of underbalanced drilling by using energized fluid. Guo et al. (1993) developed a theoretical model which considered both the carrying capacity and flowing annular pressure to determine an optimum flow rate of mud and air based on the following equation:

$$P_u = P_d + \frac{C^2}{2g_c}\left(\frac{1}{\rho_{fd}} - \frac{1}{\rho_{fu}}\right) \tag{5–11}$$

where:

$$C = \frac{M}{A}$$

$$\rho_f = \frac{a}{\frac{btz}{P} + Q_m + Q_c}$$

$$a = \frac{\gamma_g b}{53.34} + \rho_m Q_m + \rho_c Q_c$$

$$b = \frac{Q_{gsc} P_{sc}}{Z_{sc} T_{sc}}$$

A = cross sectional area of conduit, $\text{ft}^2 [M^2]$
g_c = Newton's-law conversion factor, ft - lbm / lbf - s2
M = mass flow rate, lb / s[kg / s]
P = pressure, psi[Pa]
P_d = downstream pressure,psi[Pa]

P_{sc} = standard condition pressure, psi[Pa]
Pu = upstream pressure, psi[Pa]
Q_c = volumetric flow rate of cuttings, cfpm[cmpm]
Q_{gsc} = gas flow rate under standard conditions, cfpm[cmpm]
Q_m = mud flow rate, gpm[cmpm]
ROP = rate of penetration, ft/hr[cmpm]
T = temperature, ∘R[∘K]
T_{sc} = standard condition temperature, ∘R[∘K]
z = gas compressibility factor, dimensionless
z_s = z-factor under upstream conditions
γ_g = specific gravity of gas, 1.0 for air
ρ_c = density of cuttings, lb/ft^3 $[kg/M^3]$
ρ_f = density of fluid (mixture), lb/ft^3 $[kg/M^3]$
ρ_g = density of gas, lb/ft^3 $[kg/M^3]$
ρ_m = density of mud, lb/ft^3 $[kg/M^3]$
Z_{gc} = Z-factor at standard conditions

Adewumi and Tian (1992) presented a theoretical correlation for the drag force of cuttings in air drilling as follows:

$$F_D = \frac{3}{4}\frac{C_D \rho_g (V_g - V_s)|V_g - V_s|(1-\alpha_g)\alpha_g^{-2.67}}{d_p} \tag{5–12}$$

where:

C_D = drag coefficient
d_p = particle diameter
F_D = drag-force team
V_g = gas-phase velocity
V_s = particulate phase vleocity
α_g = gas volume fraction
μ_g = gas viscosity
ρ_g = gas density

$$C_D = \begin{cases} \frac{24}{N_{Re}}\left(1.0 + 0.15 N_{Re}^{-0.687}\right) & \text{for viscous regim e, } (N_{Rc} < 1000) \\ 0.44 & \text{for Newton's regime, } (N_{Re} \geq 1000) \end{cases}$$

and

$$N_{Rc} = \frac{\rho_g (V_g - V_s) d_p}{\mu_g}$$

Most recently, Rommetveit (1995) developed a model for underbalanced drilling with coiled tubing which considered multiphase hydraulics, cuttings transport, and reservoir-wellbore interaction. However, Rommetveit's model only considered one dimension: the vertical direction.

These solutions, however, all use empirical or semi-empirical approaches. Therefore, without the additional variables, the equations can only simulate the air volume requirements. Furthermore, these equations can solve only specific cases since they were derived from specific experimental conditions. For example, Angel's (1957) (Equation 5–1) assumes a constant velocity air flow of 3000 ft/min. for all operating conditions. This assumption, of course, is not necessary true, and may cause significant errors (Adewumi and Tian 1989). The results from other approaches are valid over limited ranges of drilling parameters (Tian and Adewumi 1990) because there are so many variables involved in underbalanced drilling (Ikoku et al. 1980). Researchers have found that none of the existing models can accurately predict underbalanced drilling hydraulics. This includes air, foam, and aerated-mud drilling (Supon and Adewumi 1991). Therefore, in order to effectively perform underbalanced drilling, there is a need to develop accurate predictive models to quantify drilling pressure drop and minimum flow rate for hole clean.

6.0 RECOMMENDATIONS

Underbalanced drilling offers some unique advantages: increased productivity through a decrease in permeability damage to the producing interval, and increased penetration rate. This method will be particularly applicable to mature fields, underpressured reservoirs, and reservoirs having water-sensitive producing zones. However the major reasons why underbalanced drilling does not find more wide spread application is due to inadequate modeling. To maintain an at-balanced or slightly underbalanced condition, the industry needs a better understanding of the rheology of drilling fluids and wellbore hydraulics. There are fledging efforts to model underbalanced drilling, especially foamed drilling muds, but it is not clear that these issues will be addressed, nor if they will be available to independents with limited financial resources.

7.0 SUMMARY

Table 6.1 lists the major advantages of drilling underbalanced. Underbalanced drilling is one of the most effective ways to reduce or eliminate formation damage and control lost circulation. Recent advances in technology have made underbalanced drilling a safe and economical means for exploiting reservoirs, particularly matured reservoirs with low formation pressures. However, the technology is still in its early stages of development. One major setback in the use of underbalanced drilling is the lack of understanding of the physics of wellbore hydraulics associated with energized-drilling fluids and the absence of a proven predictive model to analyze and design drilling operations. Because poor understanding of wellbore hydraulics is involved, the operating conditions are not optimal and, consequently, costs are higher in terms of rig time, personnel time, and equipment. Properly designed underbalanced drilling can prevent drilling damage and lower completion costs. Accurate predictive modeling is a key requirement for any underbalanced drilling operation, particularly for underbalanced horizontal drilling.

Currently, none of the existing models can accurately predict underbalanced drilling hydraulics (this includes drilling with air, foam, and aerated mud). In order to effectively perform underbalanced drilling, the downhole pressure drop and minimum flow rate needed to remove cuttings must be adequately quantified. Development of improved models will require experimental work to generate the needed input parameters.

Table 6–1 Advantages of Underbalanced Drilling

Technique	Advantages	Disadvantages	Fluid Composition
Overbalanced	• Better mechanical wellbore stability • Operationally simpler		Liquid (aqueous and/or hydrocarbon)
Underbalanced	• Loss circulation control • Increased penetration rate • Reduced formation damage-increased production • Eliminates differentially stuck pipe • Reduced chemical incompatibilities		Gas/liquid mixture
Air	• Maximum penetration rate (5–6 times conventional) • No additives (cost savings) • Better cement jobs	• Not applicable in water-producing zones • Downhole fires possible • High gas rate can cause erosion • Formation spalling potential	100% gas
Mist	• Will accommodate some water influx	• Must establish correct water, surfactant, air ratio • Downhole fires possible • Formation spalling potential	Gas continuous phase Less than 10% liquid.
Foam	• Will handle more water production • Good cuttings transport • Variable degree of underbalance • Lower annual velocity, pressure drop	• Produced fluids can destabilize foam • Must know fluids characteristics (rheology, flow mechanism)	Aqueous continuous phase Gas between 50 and 90 vol. %
Aerated	• Will accommodate high water influx • Will accommodate mud-pulse MWD (parasite and microannulus injection)	• Complex heterogeneous phase flow • Complex wellbore configuration • Can be more costly	Gas entrained in liquid Less than 50% gas

8.0 REFERENCES

Adewumi, M. A., and S. Tian. 1989. Hydrodynamic Modeling of Wellbore Hydraulics in Air Drilling. SPE Paper 19333 presented at the 1989 SPE Eastern Regional Meeting, Morgantown, WV.

Adewumi, M. A., S. Tian, and R. W. Watson, 1993. Fundamental Study Makes Improves Air Drilling Possible. SPE Paper 26893 presented at the 1993 Eastern Regional Conference & Exhibition, Pittsburgh, Pennsylvania, November 2–4 .

Angel, R. C. 1957. Volume Requirements for Air or Gas Drilling *Petroleum Transactions, AIME* 210: p. 325.

Bowen, R. C, and W. G. Parkhouse. 1978. Air Drilling Scores High in Iran. *Petroleum Engineer International* September: p. 106–111.

Carden, Richard S. 1991. Air Drilling Has Some Pluses For Horizontal Wells. *Oil & Gas Journal* April 8: p. 76–8.

Carden, R. S. 1993. *Technology Assessment of Vertical and Horizontal Air Drilling Potential in the United States.* Final Report for US DOE, DOE/MC/28252-3514, August 18.

Clark, R. K., and K. L. Bickham. 1994. A Mechanistic Model for Cutting Transport. SPE paper 28306 presented at the SPE 69th Annual Technical Conference & Exhibition, New Orleans, Louisiana, September 25–26.

Claytor, S. B., K. J. Manning, and D. L. Schmalzried. 1991. Drilling a Medium-Radius Horizontal Well With Aerated Drilling Fluid: A Case Study. Paper SPE/IADC 21988, presented at the SPE/IADC Drilling Conference, Amsterdam, March 11–4.

Collins. G. 1994. Proper Planning Improves Flow Drilling. *World Oil* October: 43–50.

Cooney, M. F., T. Rogers, E. S. Stacey, and R. N. Stephens. 1991. Case History of an Opposed-Bore, Dual Horizontal Well in the Austin Chalk Formation of South Texas. Paper SPE/IADC 21985, presented at the SPE/IADC Drilling Conference, Amsterdam, March 11–4.

Dareing, Don W., and James R. Kelsey. 1981, Balanced Pressure Techniques Applied to Geothermal Drilling. *Geothermal Resources Council Transactions* (October): p. 233–6.

Dupont, J. 1984. Foam Used to Drill, Gravel-Pack, Deep Gas Well. *Oil & Gas Journal* May 7: p. 188.

Etherington, Darrell. 1994. The Rotating Control Head and Its Importance of Emerging and New Technology and Challenges of the 1990s. 6th Annual International Conference on Horizontal Well Technology, Multilaterals, Underbalanced Drilling and Emerging Technology, Houston, TX, October 24–26.

Falk, K., and C. McDonald. 1995. An Overview of Underbalanced Drilling Application in Canada. Paper SPE 30129 presented at the European Formation Damage Conference, held in The Hague, The Netherlands, May 15–6.

Grace, Robert D., and Richard S. Carden. 1995. Air & Gas Drilling Seminar, Amarillo, TX, September 18–22.

Gregory, Adrian. 1995. The Department of Trade and Industry's Improved Oil Recovery Program for the North Sea. Presented at NIPER, Bartlesville, OK, May 1.

Guo, B., G. Hareland, and J. Rajtar. 1993. Computer Simulation Predicts Unfavorable Mud Rate and Optimum Air Injection Rate for Aerated Mud Drilling. SPE Paper 26892 presented at the 1993 Eastern Regional Conference & Exhibition, Pittsburgh, Pennsylvania, November 2–4.

Ikoku, C. U., J. J. Azar, and C. R. Williams. 1980. Practical Approach to Volume Requirements for Air and Gas Drilling SPE Paper 9445, presented at the 55th Annual Fall Technical Conference and Exhibition, Dallas, TX, September 21–4.

Joseph, Robert A. 1995A. Planning Lessens Problems, Gets Benefits of Underbalance: Underbalanced Horizontal Drilling—1. *Oil & Gas Journal* March 20: p. 86–9.

Joseph, Robert A. 1995B. Special Techniques and Equipment Reduce Problems: Underbalanced Horizontal Drilling—Conclusion. *Oil & Gas Journal* March 27: p. 41–7.

Kitsios, E., H. Kamphuis, V. Quaresma, J. W. Rovig, and E. Reynolds. 1994. Underbalanced Drilling Through Oil Production Zones with Stable Foam in Oman. IADC/SPE Paper 27525 presented at the 1994 IADC/SPE Drilling Conference, Dallas, Texas, February 15–18.

Lloyd, Warren, and Steve Scherschel. 1993. Underbalanced Drilling with Coiled Tubing Paper 93-304, presented at CADE/CAODC Spring Drilling Conference, Calgary, Alberta, Canada, April 14–16.

Lunan, Brian. 1994. Underbalanced Drilling—Two Case Histories, Western Canadian Basin 6th Annual International Conference on Horizontal Well and Emerging Technologies, Houston, TX, October 24–26.

Lunan, Brian. 1995. Underbalanced Drilling Techniques Using A Closed System To Control Wells—Western Canadian Basin Case Histories. 3rd Annual International Management Conference on Coiled Tubing, Dallas, TX, February 6–8.

Machado, C. J., and C. U. Ikoku. 1982. Experimental Determination of Solids Fraction and Minimum Volumetric Requirements in Air and Gas Drilling. *Journal of Petroleum Technology* 34 (November): p. 2645–55.

Martin, D. J. 1953. *Additional Calculations to Determine Volumetric Requirements of Air or Gas as Circulating Fluid in Rotary Drilling.* Bulletin 23-A, Hughes Engineering, Houston (June 15).

Okpobiri, G. A., and C. U. Ikoku. 1986. Volumetric Requirements for Foam and Mist Drilling Operations. *SPE Drilling Engineering* February: p. 71–88.

Parkhouse, William G., and H. A. Teesdale. 1984. Air Drilling Speeds Three Tunisian Operations. *Oil & Gas Journal* September: p. 104–9.

Raza, S.H. 1965. The Streaming Potential of Foam. Ph.D. dissertation, Stanford University, Palo Alto, CA.

Rommetveit, R., E. H. Vefring, and Z. Wang. 1995. A Dynamic Model for Underbalanced Drilling with Coiled Tubing. SPE paper 29363 presented at the 1995 SPE/IADC Drilling Conference, Amsterdam, Feb. 28–Mar 2.

Shale, L. 1995. Underbalanced Drilling with Air Offers Many Pluses. *Oil & Gas Journal* June 26: 33–9.

Supon, S. B., and M. A. Adewuml. 1991. An Experimental Study of the Annulus Pressure Drop in a Simulated Air-Drilling Operation. *SPEDE* March: p. 74–80.

Teel, M. 1995. Psuedo-Underbalanced Drilling and Beyond. *World Oil* April 29.

Tian, S., and M. A. Adewumi. 1990. Analysis of Air Drilling Hydraulics. SPE Paper 21277, presented at the SPE Eastern Regional Meeting, Columbus, Ohio, Oct 31–Nov 2.

Wilson, Gilbert M. 1951. Gas Replaces Drilling Mud in San Juan Basin Operations. *World Oil* August: p. 128–39

Wolcott, D. S., and M. P. Sharma. 1986. Analysis of Air-Drilling Circulation Systems with Application to Air Volume Requirement Estimation. SPE paper 15950 presented at the 1986 SPE Eastern Regional Meeting, Columbus, OH, Nov. 12–4.

Slimhole Special Edition 1994. Slimhole Directional and Sidetrack Drilling. *Oilfield Bulletin, Schlumberger Technology News*, p. 3, insert in *Oil and Gas Journal* July 25.