Drilling Problems and Solutions

During drilling operations, some type of a drilling problem will almost certainly occur, even in very carefully planned wells. The reason is that geological conditions for two wells that are near each other may differ (nonhomogeneous formation); therefore, different problems can be encountered.

The key to success in achieving well objectives is to design drilling programs based on anticipation of potential hole problems, rather than on containment and caution. Drilling problems, when encountered, can be very costly, the most prevalent of which are:

- ***Pipe sticking***
- ***Lost circulation***
- ***Hole deviation***
- ***Pipe failures***
- ***Borehole instability***
- ***Mud contamination***
- ***Formation damage***
- ***Hole cleaning***
- ***Hydrogen sulfide–bearing formations and shallow gas***
- ***Equipment- and personnel-related problems***

An understanding of these problems, their causes, their anticipation and planning for solutions is essential to control overall well cost control and succeed in reaching the intended target zone. This chapter addresses these problems, possible solutions, and when applicable, preventive measures.

Pipe Sticking

Definition:

In drilling operations, a pipe is considered stuck if it cannot be freed (pulled out of the hole) without damage to the pipe and without exceeding the maximum allowed hook load of the drilling rig. There are two types of pipe sticking problems:

- ***Differential pressure pipe sticking***
- ***Mechanical pipe sticking***

Differential pressure pipe sticking

Differential pressure pipe sticking occurs when a portion of the drill string becomes embedded into a mud cake (an impermeable film of fine solids) that forms on the wall of a permeable formation during the drilling process. If the mud pressure, P_m, that acts on the outside wall of the pipe is greater than the formation fluid pressure, P_{ff}, as is generally the case except in underbalanced drilling, then the pipe is said to be differentially stuck, as shown in figure 1.

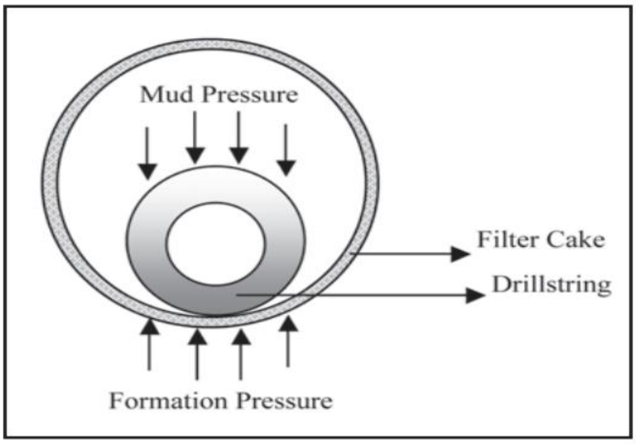

Fig. 1. Differential pressure pipe sticking

The differential pressure acting on the portion of the drill pipe that is embedded into the mud cake can be expressed as follows: $\Delta P = P_m - P_{ff}$. The ***pull force***, F_{pull}, that is required in order to free the stuck pipe is a function of the differential pressure, ΔP; the coefficient of friction, μ; and the total contact area, A_c, between the pipe and mud cake surfaces:

$$\mathbf{F_{pull} = \mu A_c \Delta P} \quad \text{-- (1)}$$

The ***coefficient of friction***, μ, can vary from less than 0.04, for oil-based muds, to as much as 0.35, for weighted water-based muds with no lubricants added. The ***contact area***, A_c, can be expressed in terms of the arc length, Ψ_{arc}, and length of the pipe body portion, L_{ep} (fig. 2) that are embedded in mud cake. The *arc length* is given as follows:

$$\psi_{arc} = 2\sqrt{\left(\frac{D_h}{2} - t_{mc}\right)^2 - \left(\frac{D_h}{2} - t_{mc}\frac{D_h - t_{mc}}{D_h - D_{op}}\right)^2} \quad \text{--- (2)}$$

D_{op} must be equal to or greater than $2t_{mc}$ and equal to or less than

$(D_h - t_{mc})$ where

D_h is the hole diameter

D_{op} is the outer pipe diameter

t_{mc} is the mud cake thickness

In equation (2), D_{op} must be equal to or greater than $2t_{mc}$ and equal to or less than $D_h - t_{mc}$. Thus, the contact area can be expressed as follows:

$$A_c = \Psi_{arc}\ L_{ep} \quad \text{--- (3)}$$

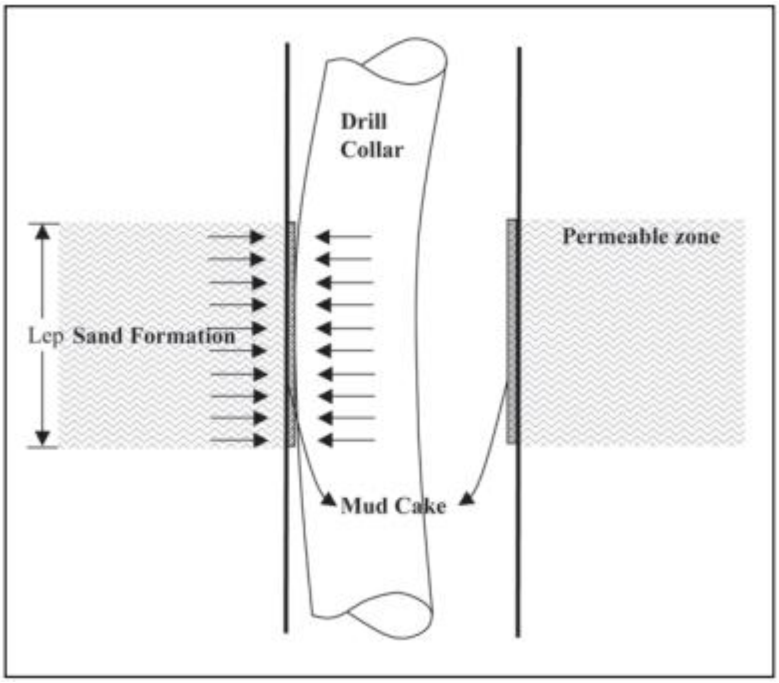

Fig.2. Differential pressure pipe sticking with embedded pipe length

Equations (1)–(3) show controllable parameters that will cause higher pipe sticking force and the potential inability of freeing the stuck pipe. These are:

• Unnecessary high differential pressure

• Thick mud cake (high continuous fluid loss to formation)

• Low-lubricity mud cake (high coefficient of friction)

• Excessive embedded pipe length in mud cake (time delay in freeing operations)

Although hole and pipe diameters and hole angle play a role in the pipe-sticking force, they are uncontrollable variables. Once they are selected to meet well design objectives, they cannot be altered. However, the shape of drill collars, as in square drill collars and drill collars with spiral grooves and external upset tool joints, can minimize the sticking force.

Some of the indicators of differential pressure stuck pipe while drilling permeable zones or known depleted-pressure zones are:

• Increase in torque and drag
• Inability to reciprocate the drill string and, in some cases, difficulty in rotating it
• Drilling-fluid circulation is not interrupted

Differential pressure pipe sticking can be prevented—or its occurrence can at least be mitigated—if some or all of the following precautions are taken:

• Maintain the lowest continuous fluid loss while adhering to the project economic objectives (e.g., controlling the mud cake thickness)
• Maintain the lowest amount of drilled solids in the mud system or, if economical, remove all drilled solids
• Use lowest differential pressure, with allowance for swab and surge pressures during tripping operations
• Select a mud system that will yield smooth mud cake (low coefficient of friction)
• Maintain drill string rotation at all times, if possible

As stated earlier, differential pressure pipe sticking problems may not be totally prevented. Therefore, when the problem does occur, common field practices for freeing the stuck pipe include

• Mud hydrostatic pressure reduction in the annulus
• Oil spotting around the stuck portion of the drill string
• Washing over the stuck pipe

Some of the methods used to reduce the hydrostatic pressure in the annulus are:

• Reduction of mud weight by dilution

• Reduction of mud weight by gasifying with nitrogen

• Placement of a packer in the hole above the stuck point

Example 1

You are given the following well data:

• Drill collar outer diameter: D_{op} = 6.0 in.

• Hole diameter: D_h = 9.0 in.

• Mud cake thickness: t_{mc} = 2/32 in.

• Coefficients of friction: 0.15, for oil-based mud; 0.25, for water-based mud

• Length of drill collar embedded in mud cake: L_{ep} = 20 ft = 240 in.

• Differential pressure: ΔP = 500 psi

• Determine the required pull force to possibly free the stuck pipe

***Solution**:*

By use of equation (2), the arc length is found: ψ_{arc} = 2.1 in. By use of equation (1), the pull force is then calculated:
for the coefficient of friction 0.15,

$F_{pull} = 0.15 \times 500 \times 2.1 \times 240 = 37{,}530$ lbs; for the coefficient of friction 0.25

$F_{pull} = 0.25 \times 500 \times 2.1 \times 240 = 62{,}550$ lbs

Mechanical pipe sticking

The causes of mechanical pipe sticking include:

• High accumulation of drilled cuttings in the annulus

• Borehole instabilities—such as hole caving, sloughing, or collapse and plastic shale or salt sections squeezing (narrowing)

• Key seating

Drilled cuttings

Excessive drilled-cuttings accumulation in the annular space owing to inadequate hole cleaning can cause mechanical pipe sticking—particularly in directional well drilling, in which a stationary cuttings bed may form on the low side of the borehole. If this condition exists while tripping out, pipe sticking is very likely imminent. This is why it is a common field practice to circulate bottom up several times, with the drill bit off bottom, to flush out any cuttings bed that may be present prior to making a trip. A trend of increasing torque and drag and sometimes circulating drill pipe pressure is an indication of large accumulations of cuttings in the annulus and potential mechanical pipe-sticking problems. Some preventives measures include:

- Proper hydraulics and/or mud viscosity to maintain turbulent flow in annulus
- Drill string rotation at high enough speed to agitate any stationary cuttings bed that may have formed on the low side of the borehole

Borehole instability

This topic is addressed in more detail later; however, it is important at this time to mention, in brief, the pipe-sticking issues that are associated with the borehole instability problems. The most troublesome problem is posed by drilling into shale. Depending on mud composition and mud weight, shale can slough or plastically flow inward and therefore causes mechanical pipe sticking. In all types of formations, using too low of a mud weight can lead to the collapse of the hole, possibly causing mechanical pipe sticking. Also, drilling through salt that is known to exhibit plastic behavior under the overburden pressure can lead to problems. If mud weight is not high enough, the salt has the tendency to flow inward, causing mechanical pipe sticking. Indications of potential pipe-sticking problems due to borehole instability are a rise in circulating drill pipe pressure, an increase in torque, and in some cases, no fluid return to surface. (See fig. 3.).

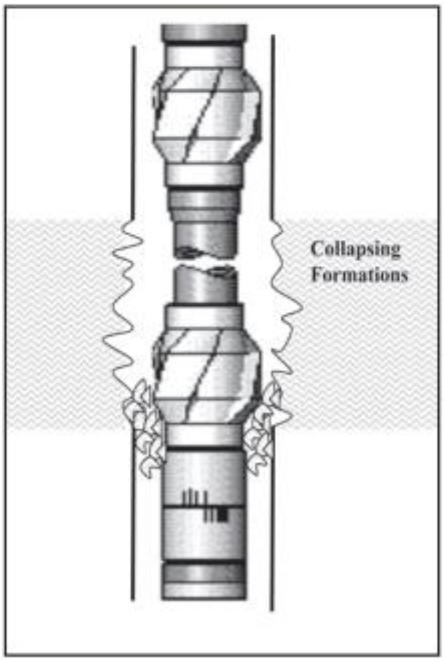

Fig.3. Pipe sticking due to wellbore instability

Key seating.

It is well known that *key seating* is a major cause of mechanical pipe sticking (fig. 10–4). The mechanics of key seating involve wearing a small hole (groove) into the side of a full-gauge hole. This groove is caused by drill string rotation with side force acting on it. This condition is created in either doglegs or undetected ledges in the vicinity of washouts.

The lateral force that tends to push the pipe against the wall that causes mechanical erosion and thus creates a key seat is given by $F_L = T_{\sin\theta dl}$, where F_L is the lateral force, T is the tension in the drill string just above the key seat area, and θ_{dl} is the abrupt change in hole angle (commonly referred to as the dogleg angle).

In general, long bit runs can cause key seats; therefore, it is common practice to make what is called wiper trips. Also, use of stiffer BHAs tends to minimize severe dogleg occurrences. During tripping out of the hole, a key-seating pipe-sticking problem is evident when several stands of pipe have been pulled out and then, all of a sudden, the pipe becomes stuck.

Freeing mechanically stuck pipe is achieved in many ways, depending on the suspected cause of sticking. For example, if cuttings accumulation is suspected to be the cause, then rotating and reciprocating the drill string and increasing the flow rate without exceeding the maximum allowed ECD are possible remedies for freeing the pipe. If hole narrowing owing to plastic shale is the cause, then an increase in mud weight may free the pipe, whereas hole narrowing owing to salt is the cause, then circulation of freshwater may free the pipe.

By contrast, if pipe is stuck in a key seat area, the most successful solution is backing off below the key seat and going back into the hole with an opener, to drill out the key section. Consequently, this will leads to a fishing operation, to retrieve the fish. The decision on how long to continue attempting to free stuck pipe versus back off, plug back, and then sidetrack is an economic issue that is generally addressed by the operating company.

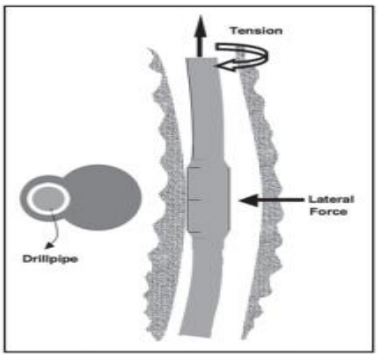

Fig.4. Pipe sticking due to key seating

Loss of Circulation

Definition

Lost circulation is defined as the uncontrolled flow of whole mud into a formation, sometimes referred to as a thief zone. The loss can be partial or total, as shown in figure 5. In partial lost circulation, mud continues to flow to surface with some loss to the formation. Total loss circulation, however, is when all the mud flows into a formation with no return to surface. In total loss circulation, if drilling is allowed to continue, it is referred to as blind drilling. This is not a common practice in the field, unless the formation above the thief zone is mechanically stable (i.e., there is no production and the fluid is clear water) and it is feasible, in terms of economics and safety, to go ahead with the drilling operation.

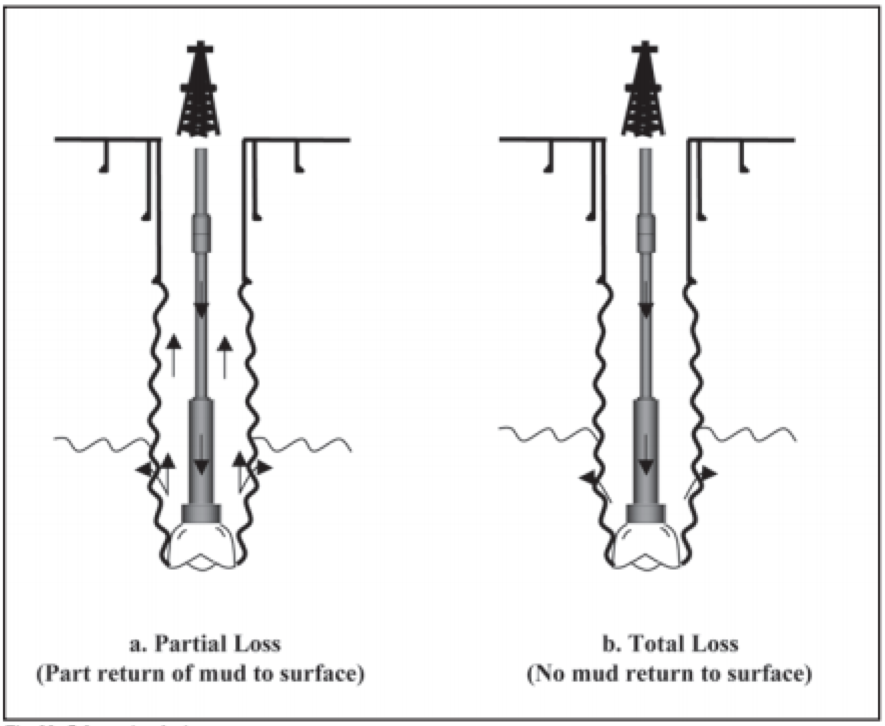

Fig.5. Lost circulation

Lost circulation zones and causes

Formations that are inherently fractured, depleted, or cavernous or have a high permeability, on the one hand, are potential zones of lost circulation. On the other hand, under certain improper drilling conditions, induced fractures become potential zones of lost circulation. The major causes of induced fractures are excessive downhole pressures and improper intermediate casing-setting depth, especially in the transition zone.

Induced or inherent fractures may be horizontal at shallow depth or vertical at depths greater than approximately 2,500 ft. Excessive wellbore pressures are caused by high flow rates (high annular friction pressure loss) or tripping in too fast (high surge pressure), which can lead to high ECD. In addition, as a result of improper annular hole cleaning, excessive mud weight, or shutting a well in high pressure, shallow gas can also induce fractures and therefore cause lost circulation. Equations (4) and (5) show the conditions that must be maintained to avoid fracturing the formation during drilling and tripping in, respectively:

$(ECD)_{drilling} = \rho_{eq} = \rho_m + \Delta\rho_f < \rho_{frac}$ -------------------------------- (4)

$(ECD)_{tripping\ in} = \rho_{eq} = \rho_m + \Delta\rho_{srg} < \rho_{frac}$ ------------------------------ (5)

Where:

ρ_m is the static mud weight

$\Delta\rho_f$ is the additional mud weight owing to friction pressure loss in annulus

$\Delta\rho_{srg}$ is the additional mud owing to surge pressure

ρ_{frac} is the formation pressure fracture gradient in equivalent mud weight

ρ_{eq} is the equivalent circulating mud weight

Cavernous formations are limestone with inherently large caverns. This type of lost circulation is quick and total and is the most difficult to seal. High-permeability formations that are potential lost circulation zones are those of shallow sand of permeability in excess of 10 darcies. Generally, deep sand has a low permeability and therefore presents no loss of circulation problems. In noncavernous thief zones, mud level in mud tanks decreases gradually, and if drilling continues, total loss of circulation may occur.

Prevention of lost circulation

Complete prevention of lost circulation is not possible. This is because some formations—such as inherently fractured, low-pressure, cavernous, or high-permeability zones—are not avoidable when encountered during the drilling operation if the target zone is to be reached. However, mitigating the problem of lost circulation is possible if certain precautions, especially those related to induced fractures, are taken:

- Maintain proper mud weight
- Minimize annular friction pressure losses during drilling and tripping in
- Maintain adequate hole cleaning and avoid restrictions in the annular space
- Set casing to protect upper weaker formations during a transition zone
- Update formation pore pressure and fracture gradients for more accurate log and drilling data
- If lost circulation zones are anticipated, work out preventive measures prior to drilling that zone by treating the mud with lost circulation materials.

Remedial measures

When lost circulation occurs, sealing the zone is necessary, unless the geological conditions allow blind drilling (which is unlikely in most cases). The common lost circulation materials that are mixed with the mud to seal loss zones may be grouped as fibrous, flaked, granular, and/or a combination of the three.

These materials are available in course, medium, and fine grades for an attempt to seal low- to moderate-loss circulation zones. In the case of severe-loss circulation zones, the use of various plugs to seal the zone becomes mandatory. It is important, however, to know the location of the lost circulation zone prior to setting a plug. Various types of plugs used throughout the industry include bentonite–diesel oil squeeze, cement bentonite–diesel oil squeeze, cement, and barite.

Hole Deviation

Hole deviation is the unintentional departure of the drill bit from drilling along a preselected borehole trajectory. Whether drilling a straight or a curved hole section, the tendency of the bit to walk away from the desired path can lead to a higher drilling cost and legal problems with regard to the lease boundary. (See fig. 6.)

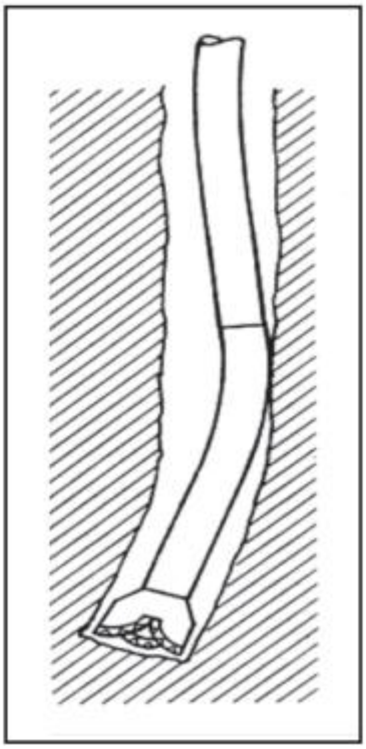

Fig.6. Wellbore deviation

Causes

It is not exactly known what causes a drill bit to deviate from its intended path. It is, however, generally agreed that one or a combination of several of the following factors may be responsible for hole deviation:

• Heterogeneous nature of formation and dip angle
• Drill string characteristics and dynamic behavior
• Applied WOB
• Hole inclination angle from vertical
• Drill bit type and basic mechanical and hydraulic design
• Hydraulics at the bit
• Improper hole cleaning

A resultant force acting on a drill bit causes hole deviation to occur. The mechanics of this resultant force is complex and is mainly governed by the mechanics of the BHA, the rock-bit interaction, bit operating conditions, and to a lesser extent, the drilling-fluid hydraulics. The forces imparted to the drill bit owing to the BHA are directly related to the makeup of the BHA, (stiffness, stabilizers, reamers, etc.).

The BHA is a flexible elastic structural member that can buckle under compressive loads. The buckled shape of a given design of BHA depends on the amount of applied WOB. The significance of the BHA buckling is that it causes the axis of the drill bit to misalign with the axis of the intended hole path, causing the deviation. Pipe stiffness and length and number of stabilizers (their location and clearances from the wall of the wellbore) are two major parameters that govern the BHA-buckling behavior. The buckling tendency of the BHA is minimized by reduction of WOB and use of stabilizers with outside diameters that are almost in gauge with the wall of the borehole.

The contribution of the rock-bit interaction to bit deviating forces is governed by the following factors:

• Rock properties (cohesive strength, bedding or dip angle, and internal friction angle)

• Drill bit design features (tooth angle, bit size, bit type, bit offset [in the case of roller cone bits], teeth location and number, bit profile, and bit hydraulic features)

• Drilling parameters (tooth penetration into the rock and its cutting mechanism) .

The mechanics of the rock-bit interaction is a very complex subject and is the least understood problem contributing to hole deviation. Fortunately, the advent of downhole measuring-while drilling (MWD) tools that allow the monitoring of the advance of the drill bit along the desired path has made our lack of understanding with regard to the mechanics of hole deviation more acceptable.

Drill Pipe Failures

Drill pipe failures can be categorized as follows:

• Twist-off—due to excessive torque

• Parting—due to excessive tension

• Burst or collapse—due to excessive internal pressure or external pressure, respectively

• Fatigue—due to mechanical cyclic loads, with or without corrosion

Twist-off

Pipe failure due to twist-off occurs when the induced shearing stress owing to high torque exceeds the pipe material's ultimate shear stress. In vertical well drilling, excessive torques are not generally encountered under normal drilling practices. In directional and extended-reach drilling, however, torques in excess of 80,000 ft-lbs are common and can easily cause twist-off of improperly selected drill string components.

Parting

Pipe failure due to parting occurs when the induced tensile stress exceeds the pipe material's ultimate tensile stress. This condition may arise when pipe sticking occurs and an overpull is applied in addition to the effective weight of suspended pipe in the hole above the stuck point.

Collapse and burst

Pipe failure due to collapse or burst is not common. However, under extreme conditions of high mud weight and complete loss of circulation, pipe burst may occur.

Fatigue

Fatigue is a dynamic phenomenon that may be defined as the initiation and propagation of micro-cracks into macro-cracks as a result of repeated applications of stresses. It is a process of localized progressive structural fractures in material under the action of dynamic stresses. It is well established that a structural member that may not fail under a single application of static load may very easily fail under the same load if it is applied repeatedly. Failure under cyclic (repeated) loads is referred to as fatigue failure.

Drill string fatigue is the most common and costly form of drill pipe failure in oil/gas and geothermal drilling operations. The combined action of cyclic stresses and corrosion can shorten the life expectancy of a drill pipe by a factor of thousands. Cyclic stresses are induced by dynamic loads owing to drill string vibrations and bending load reversals in curved sections of hole and doglegs owing to rotation. Pipe corrosion occurs during the presence of oxygen, carbon dioxide, chlorides, and/or hydrogen sulfide (H2S). H2S is the most severely corrosive element to steel pipe and is deadly to humans. Regardless of what may have caused pipe failure, the cost of fishing operations—and, sometimes, unsuccessful attempts to retrieve the fish out of the hole—can lead to the loss of multiple millions of dollars owing to rig downtime, the loss of expensive tools down hole, or the abandonment of the already-drilled section below the fish.

In spite of the vast amount of work that has been dedicated to pipe fatigue failure, it is still the least understood in terms of accurate analysis. This lack of understanding is attributed to the wide variations of statistical data in determining

- Type of service and environment of the drill string
- Magnitude of operating loads and frequency of occurrence (i.e., load history)
- Accuracy of methods to quantify the stresses
- Quality at time of manufacture (i.e., quality control)
- Applicability of material fatigue data

Pipe failure prevention

Although pipe failures cannot be totally eliminated, certain measures can be taken to minimize it. Fatigue failures can be mitigated by the minimization of induced cyclic stresses and by ensuring a noncorrosive environment during drilling operations. Cyclic stresses can be minimized by controlling dogleg severity and drill string vibrations. Corrosion can be mitigated by corrosive scavengers and by controlling the mud pH in the presence of H2S. Proper handling and inspection of the drill string on a routine basis are the best measures for the prevention of failures.

Borehole Instability

Definition and causes

Borehole instability is an undesirable condition of an open hole interval that does not maintain its gauge size and shape and/or its structural integrity. The causes may grouped into the following categories:

- Mechanical—due to *in situ* stresses
- Erosion—due to fluid circulation
- Chemical—due to interaction of borehole fluid with the formation

Problems associated with borehole instabilities

There are four different types of borehole instabilities, as shown in figure (7) including:

- Hole closure or narrowing
- Hole enlargement or washouts
- Fracturing
- Collapse

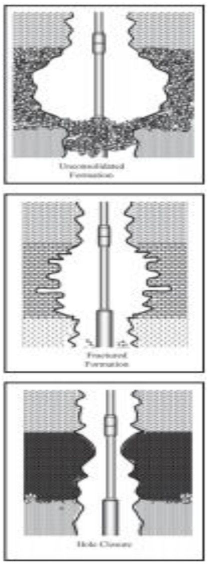

Fig.7. Borehole instability–associated problems

The problems associated with each type are addressed in the following sections.

Hole closure

Hole closure is a time-dependent process of borehole narrowing, sometimes referred to as creep, under the overburden pressure. It generally occurs in plastic flowing shale and salt sections. The associated problems are:

• Increase in torque and drag

• Increase in potential for pipe sticking

• Increase in difficulty of casings landing

Hole enlargement

Hole enlargements are commonly termed washouts; that is, the hole becomes undesirably larger than intended. Hole enlargements are generally caused by hydraulic erosion and mechanical abrasion owing to the drill string and in inherently sloughing shale. The associated problems are:

• Increase in difficulty of cementing

• Increase in potential for hole deviation

• Increase in hydraulics requirements for effective hole cleaning

• Increase in potential for problems during logging operations

Fracturing

Fracturing occurs when the wellbore drilling-fluid pressure exceeds the formation fracture pressure. The associated problems are:

• Lost circulation

• Possible kick occurrence

Collapse

Borehole collapse occurs when the drilling-fluid pressure is too low to maintain the structural integrity of the drilled hole. The associated problems are:

- Pipe sticking
- Possible loss of well

Principles of borehole instability

Before drilling, the rock strength at some depth is in equilibrium with the *in situ* rock stresses (effective overburden stress and effective horizontal confining stresses). While a hole is being drilled, however, the balance between the rock strength and the *in situ* stresses is disturbed. In addition, foreign fluids are introduced, and an interaction process begins between the formation and borehole fluids. The result is the potential for a hole instability problem to arise. Although a vast amount of research has resulted in many borehole stability simulation models, all share the same shortcoming, of uncertainty in input data needed to run the analysis. Such data include *in situ* stresses, pore pressure, formation fluid chemistry (in the case of shale), and rock mechanical properties.

Mechanical rock failure mechanisms

Mechanical borehole failure occurs when the stresses acting on the rock exceed the compressive strength or the tensile strength of the rock. Compressive failure is caused by shear stresses as a result of low mud weight, whereas tensile failure is caused by normal stresses as a result of excessive mud weight. The following failure criteria are used to predict hole instability problems:

- Maximum normal stress—for tensile failure
- Maximum strain energy of distortion—for compressive failure

In the maximum normal stress criterion, failure is said to occur when, under the action of combined stresses, one of the acting principal stresses reaches the failure value of the rock tensile strength. In the maximum of energy of distortion criterion, failure is said to occur when, under the action of combined stresses, the energy of distortion reaches the same energy of failure of the rock under pure tension.

Shale instability

Over 75% of drilled formations worldwide are shale formations. The drilling cost attributed to shale instability problems has been reported to be in excess of half a billion U.S. dollars per year. The causes of shale instability are twofold:

- Mechanical (stress change vs. shale strength environment)
- Chemical (shale/fluid interaction: capillary pressure, osmotic pressure, pressure diffusion, and borehole fluid invasion into shale)

Mechanical instability

As stated previously, mechanical rock instability can occur because the *in situ* stress state of equilibrium has been disturbed after drilling. The density of the mud in use may not bring the altered stresses to the original state; consequently, shale may become mechanically unstable.

Chemical instability

Chemical-induced shale instability due to the drilling-fluid/shale interaction alters shale strength, as well as the pore pressure in the vicinity of the borehole walls. This is caused by several mechanisms, including

- Capillary pressure

- Osmotic pressure
- Pressure diffusion in the vicinity of the borehole walls
- Borehole fluid invasion into the shale in overbalanced drilling

Capillary pressure

During drilling, the mud in the borehole contacts the native pore fluid in the shale through the pore throat interface, resulting in the development of capillary pressure, P_{cap}. which is expressed as:

$$P_{cap} = \frac{2\lambda\cos\theta}{r}$$ -- (6)

Where

λ is the interfacial tension

θ is the contact angle between the two fluids

r is the pore throat radius

To prevent borehole fluids from entering the shale and hence to stabilize the borehole, an increase in capillary pressure is required. This can be achieved by using oil-based or other organic low-polarity mud systems.

Osmotic pressure

When the energy level (referred to as the activity), *A*s, in shale pore fluid is different than the energy level, *A*m, in drilling mud, movement of water can occur in either direction across a semipermeable membrane, as a result of the development of osmotic pressure, p_{os}, or chemical potential, P_c. To prevent or reduce water movement across this semipermeable membrane that has a certain efficiency, E_m, one needs to equalize the activities or at least minimize their differential. If A_m is lower than A_s, it is suggested to increase E_m, and vice versa. The mud activity can be reduced by the addition of electrolytes that can be brought about through the use of mud systems such as seawater, saturated-salt polymer, KCl/NaCl polymer, and lime/gypsum.

Pressure diffusion

Pressure diffusion is a phenomenon of pressure change near the borehole walls that occurs over time. This pressure change is due to the compression of the native pore fluid by the borehole fluid pressure, p_{wfl}, and the osmotic pressure, p_{os}.

Borehole fluid invasion into shale

In conventional drilling, a positive differential pressure (difference between the borehole fluid pressure and the pore fluid pressure) is always maintained. As a result, borehole fluid is forced to flow into the formation (fluid-loss phenomenon) and may cause a chemical interaction that can lead to shale instabilities. To mitigate this problem, an increase of mud viscosity is generally used, although, in extreme cases, gilsonite may be used to seal off micro-fractures.

Wellbore stability analysis

There are several models in the literature that address wellbore stability analysis. These include very simple to very complex models, such as

- Linear elastic
- Nonlinear
- Elasto-plastic
- Purely mechanical
- Physico-chemical

Regardless of the model, the data needed include:

• Rock properties (Poisson ratio, strength, modulus of elasticity, etc.)

• *In situ* stresses (overburden and horizontal)

• Pore fluid pressure and chemistry

• Mud properties and chemistry

Analysis of the data (other than those data pertaining to the mud) is often confounded by problems of availability and/or uncertainties. However, sensitivity analysis can be conducted by assuming data for the many variables, to establish safety windows for mud selection and design.

Borehole instability prevention

Total prevention of borehole instability is unrealistic because restoring the physical and chemical *in situ* conditions of the rock are impossible. However, the drilling engineer can mitigate the problems of borehole instabilities by adhering to good field practices, including

• Proper selection and maintenance of mud weight

• Proper hydraulics to control the ECD

• Proper hole trajectory selection

• Compatible borehole fluid with the formation being drilled

• Minimum time spent in open hole

• Use of offset well data (utilization of the learning curve)

• Monitoring of trend changes (torque, circulating pressure, drag, fill in during tripping, etc.)

• Collaboration and sharing of information

Mud Contamination

Definition

A mud is said to be contaminated when a foreign material enters the mud system and causes undesirable changes in mud properties such as the density, the viscosity, and/or filtration. In general, water-based mud systems are the most susceptible to contamination of various types. Mud contamination can result from overtreatment of the mud system with additives or from material entering the mud during drilling.

Common contaminants—sources and treatments

The most common contaminants of water-based mud systems are

- Solids (added, drilled, active, and inert)
- Gypsum/anhydrite (Ca^{2+})
- Cement/lime (Ca^{2+})
- Makeup water (Ca^{2+} and Mg^{2+})
- Soluble bicarbonates and carbonates (HCO_3^- and CO_3^{2-})
- Soluble sulfides (HS^- and S^{2-})
- Salt/saltwater flow (Na^+ and Cl^-)

Solids contamination

Solids are those that are added to make up a mud system (e.g., bentonite and barite) and those that are drilled (all types—active and inert). Excess solids of any type are the most undesirable contaminant of drilling fluids, because they affect all mud properties. It has been shown that fine solids, of micron and submicron size, are the most detrimental to the overall drilling efficiency and must be removed if they are not a necessary part of the mud makeup.

The removal of drilled solids is achieved through the use of mechanical separating equipment (shakers, desanders, desilters, and centrifuges). Shakers remove solids of the size of cuttings (approximately 140 microns or larger). Desanders remove solids of the size of sand (down to 50 microns). Desilters remove solids in the size of silt (down to 20 microns). When solids become smaller than the cutoff point of desilters, centrifuges may have to be used. Chemical flocculants are sometimes used to flocculate fine solids into bigger size, so that they can be removed the by solids removal equipment. Total flocculants are those that do not discriminate between various types of solids, and selective flocculants are those that will flocculate drilled solids but not added barite solids. As a last resort, dilution is sometimes used to lower solids concentration.

Calcium ions contamination

The sources of calcium ions are gypsum, anhydrite, cement, lime, seawater, and hard/brackish makeup water. The calcium ion is a major contaminant to freshwater-based sodium/clay-treated mud systems. The calcium ion tends to replace the sodium ions on the clay surface through a base exchange, causing undesirable changes in mud properties such as rheology and filtration. It also causes thinners added to mud system to become ineffective. The treatment chosen depends on the source of the calcium ions. For example, sodium carbonate (soda ash) is used if the source is gypsum or anhydrite. Sodium bicarbonate is preferred if the source is lime or cement. If treatment becomes economically unacceptable, break over to a mud system that can tolerate the contaminant, such as gypsum mud or lime mud.

Bicarbonate and carbonate contamination

The contaminant ions (CO_3^{2-} and HCO_3^-) come from drilling into carbon dioxide–bearing formations, thermal degradation of organics in mud, or overtreatment with soda ash and bicarbonate. These contaminants cause the mud to have high yield and gel strength and decreased pH. Treatment of the mud system with gypsum or lime is recommended.

Hydrogen sulfide contamination

The contaminant ions (HS^-, S^{2-}) generally come from drilling into H_2S-bearing formations. Hydrogen sulfide is the most deadly contaminant ion to humans and the most corrosive ion to steel in drilling operations (causing severe embrittlement to drill pipe). Scavenging of H_2S is done through the use of zinc, copper, or iron.

Salt/saltwater flows

The ions (Na^+ and Cl^-) that enter the mud system as a result of drilling into salt sections or as a result of formation saltwater flow cause a mud to have high yield strength, high fluid loss, and decreased pH. Some actions for treatment are dilution with freshwater, use of dispersants and fluid loss chemicals, and if the cost of treatment becomes excessive, ultimate conversion to a mud that tolerates the problem.

Producing-Formation Damage

Definition

Producing-formation damage has been defined by Brent Bennion as "the impairment of the unseen by the inevitable, causing an unknown reduction in the un-quantifiable." In a different context, formation damage is defined as the impairment to a reservoir (reduced production), caused by wellbore fluids used during drilling/completion and workover operations. It is a zone of reduced permeability within the vicinity of the wellbore (skin) that results from the invasion of foreign fluid into the reservoir rock. (See fig. 8.)

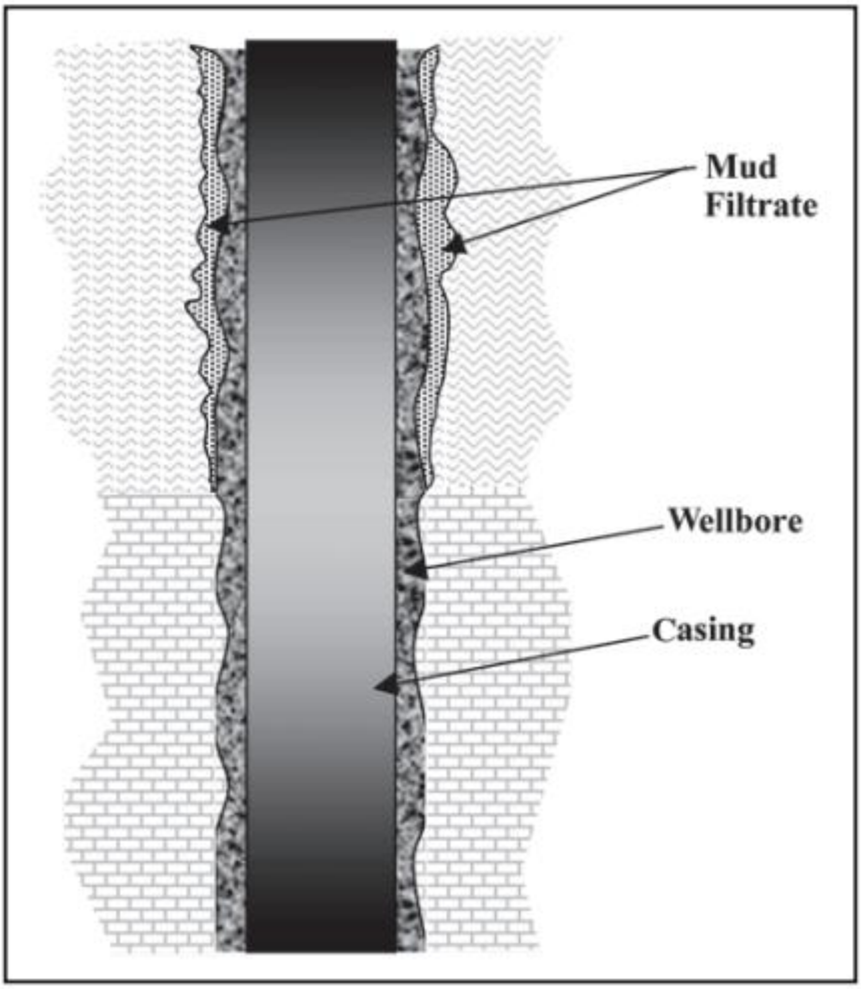

Fig. 8. Formation damage

Borehole fluids

Borehole fluids are classified as follows:

- Drilling fluids
- Completion fluids
- Workover fluids

Drilling fluids are categorized as mud, gas, or gasified mud. There are two types of mud: water based (pure polymer, pure bentonite, or bentonite/polymer) and oil based (invert emulsion or oil). Completion and workover fluids are mostly brines and solids free.

Damage mechanisms

The vast amount of literature identifies formation damage as a combination of several mechanisms:

• *Solids plugging.* Plugging of the reservoir rock pore spaces can be caused by either fine solids in the mud filtrate or dislodged solids within the rock matrix, as shown in figure 9. To minimize this form of damage is to minimize the amount of fine solids in the mud system and its fluid loss.

• *Clay particle swelling or dispersion.* This is a problem inherent in sandstone that contains water-sensitive clays. When a freshwater filtrate invades the reservoir rock, it causes the clay to swell and thus reduces or totally blocks the throat areas.

• *Saturation change.* Production is predicated on the amount of saturation within the reservoir rock. When a mud system filtrate enters the reservoir, this causes some change in water saturation and, therefore, potential reduction in production. High fluid loss causes increased water saturation, resulting in decreased rock relative permeability.

• *Wettability reversal.* Reservoir rocks are water wet in nature. It has been demonstrated that while drilling with oil-based mud systems, excess surfactants in the mud filtrate that enter the rock can cause wettability reversal. On the basis of field experience and laboratory tests, as much as 90% production loss can be caused by this mechanism. Therefore, to guard against this problem, the amount of excess surfactants used in oil-based mud systems should be kept to a minimum.

• *Emulsion blockage.* Inherent in oil-based mud systems is the use of excess surfactants. These surfactants, on entering the rock, can form an emulsion within the pore spaces, thus hindering production.

• *Aqueous filtrate blockage.* In water-based mud systems, the aqueous filtrate that enters the reservoir can cause blockage that reduces the production potential of the reservoir.

• *Mutual precipitation of soluble salts.* Any precipitation of soluble salts in the wellbore fluid filtrate, whether from the use of salt mud systems or from formation water or both, can cause solid blockage and thus hinder production.

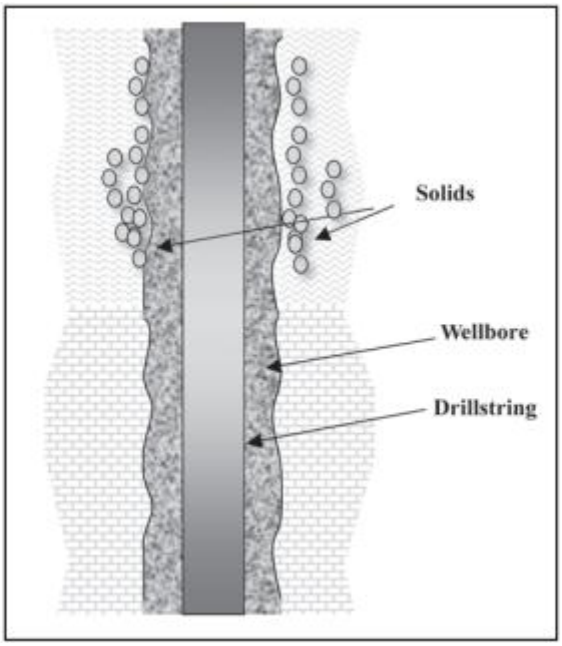

Fig. 9. Solids plugging

Hole Cleaning

Introduction to hole cleaning

Throughout the past decades, many studies have been conducted to increase our understanding of hole cleaning in directional well drilling. It has been demonstrated in laboratory work that drilling at inclination angle greater than approximately 30° from the vertical poses problems in cuttings removal that are not encountered in vertical wells. Formation of a moving or a stationary cuttings bed becomes an apparent problem if the flow rate for a given mud rheology is below a certain critical value, as illustrated in figure 10.

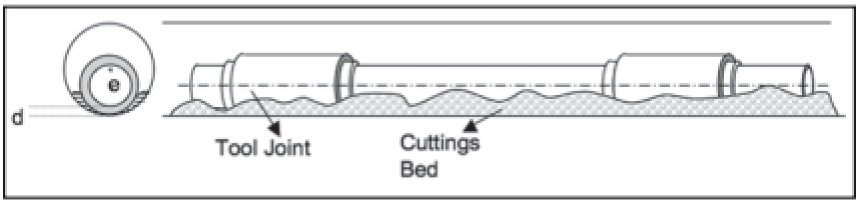

Fig.10. Bed height formation owing to inadequate hole cleaning

Inadequate hole cleaning can lead to costly drilling problems, such as

- Mechanical pipe sticking
- Premature bit wear
- Slow drilling
- Formation fracturing
- Excessive torque and drag on drill string
- Difficulties in logging and cementing
- Difficulties in casings landing

The most prevalent of these is excessive torque and drag, which often makes it impossible to reach the target in high-angle/extended-reach drilling.

Factors affecting hole cleaning

The factors that have an impact on hole cleaning (annular cuttings removal) include

- Annular fluid velocity
- Hole inclination angle
- Drill string rotation
- Annulus/pipe eccentricity

• ROP
• Drilling-fluid properties
• Drilled-cuttings characteristics

A brief discussion on each of these factors and their limitations in field situations is presented in the following sections.

Annular fluid velocity

Irrespective of all other factors that affect annular hole cleaning, the flow rate is the dominant factor in cuttings removal while drilling directional wells. An increase in flow rate will result in more efficient cuttings removal under all conditions. However, the extent to which the flow rate can be increased may be limited by the following:

• The maximum allowed ECD
• Susceptibility of the open hole section to hydraulic erosion
• Rig hydraulic power availability

Hole inclination angle

It has been demonstrated through laboratory work that as hole angle increases from 0° to about 67° from the vertical, hole cleaning becomes more difficult and, therefore, the flow rate requirement increases. The flow rate requirements reach a maximum around 65–67° and then slightly decrease toward the horizontal. Also, it has been shown that around 25–45°, a sudden pump shutdown can cause cuttings sloughing to the bottom and may result in mechanical pipe sticking.

Although hole inclination can lead to cleaning problems, it is mandated by the needs of drilling into an inaccessible reservoir, offshore drilling, avoiding troublesome formations, side tracking, and drilling horizontally into the reservoir. Company objectives in total field development (primary and secondary production), environmental concerns, and economics are some of the factors influencing hole angle selection.

Drill string rotation

It has been shown in laboratory studies and reported from field cases that drill string rotation has moderate to significant effects that enhance hole cleaning. The level of enhancement is a combined effect of pipe rotation, mud rheology, cuttings size, flow rate, and very importantly, the string dynamic behavior. It has been proved that the whirling motion of the string around the wall of the borehole as it rotates is the major contributor to hole-cleaning enhancement. Also, mechanical agitation of the cuttings bed on the low side of hole and exposure to higher fluid velocities as the pipe moves to the high side of the hole are benefits of pipe whirling action.

Although pipe rotation definitely enhances hole cleaning, there are certain limitations to its implementation. For example, during angle building while using a downhole motor (i.e., in sliding mode), rotation cannot be induced. With the new rotary steering systems, this is no longer a problem. However, pipe rotation causes cyclic stresses that can cause acceleration of pipe failures owing to fatigue, casing wear, and in some cases, mechanical destruction to open hole sections. In addition, in slim hole drilling, high pipe rotation can cause high ECDs owing to the increase in annular friction pressure losses.

Hole/pipe eccentricity

In the inclined section of hole, the pipe has the tendency to rest on the low side of the borehole, owing to gravity. This creates a very narrow gap in the annulus section below the pipe; consequently, the fluid velocity becomes extremely low, leading to an inability to transport cuttings to the surface. As illustrated in figure 11, as eccentricity increases, particle fluid velocity decreases in the narrow gap, especially for high viscosity fluid. However, since eccentricity is governed by the selected well trajectory, its adverse impact on hole cleaning may not be avoidable.

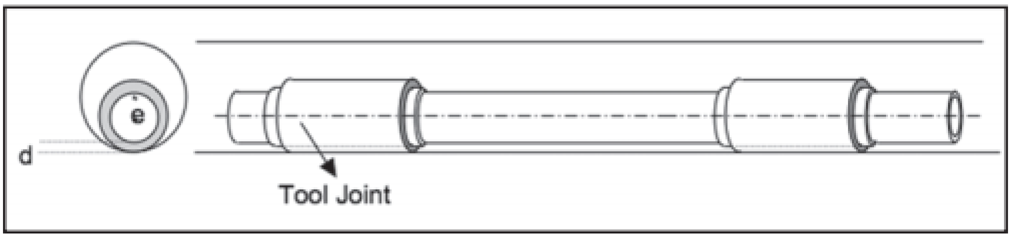

Fig.11. Hole/pipe eccentricity

ROP

Under similar conditions, an increase in the drilling rate always results in an increase in the amount of cuttings in the annulus. To ensure good hole cleaning during high ROP drilling, the flow rate and/or pipe rotation have to be adjusted. If the limits of these two variables are exceeded, the only alternative is to reduce the ROP. Although a decrease in the ROP will have a detrimental impact on the drilling cost, the benefit of avoiding other drilling problems, such as mechanical pipe sticking and excessive torque and drag, can outweigh the loss in ROP.

Mud properties

The functions of drilling fluids are many and can have unique, competing influences. The two mud properties that have a direct impact on hole cleaning are the viscosity and the density.

The main functions of density are mechanical borehole stabilization and prevention of the intrusion of formation fluids into the annulus. Any unnecessary increase in mud density, beyond fulfilling the aforementioned two functions, will have an adverse effect on the ROP and, under the given *in situ* stresses, may cause fracturing of the formation. Importantly, mud density should not be used as a criterion to enhance hole cleaning.

Viscosity has as its primary function the suspension of added desired weighting materials, such as barite. Only in vertical well drilling and high-viscous pill sweep is viscosity used as a remedy in hole cleaning.

Cuttings characteristics

The size and distribution, the shape, and the specific gravity of cuttings affect their dynamic behavior in a flowing media. The specific gravity of most rocks is around 2.6 and therefore can be assumed as a nonvarying factor in cuttings transport. The cuttings size and shape are functions of the bit types (roller cone, PDC, or diamond matrix), of the regrinding that takes place after they are generated, and further of breakage by their own bombardment and bombardment with the rotating drill string. Thus, it is impossible to control the size and shape of cuttings, even if a specific bit group has been selected to generate them. Note that smaller cuttings are more difficult to transport in directional well drilling; however, with some viscosity and pipe rotation, fine particles seem to stay in suspension and therefore are easier to transport.

Hydrogen Sulfide–Bearing Zones and Shallow Gas

Hydrogen sulfide–bearing formation drilling poses one of the most difficult and dangerous problems to humans and equipment. If the presence of hydrogen sulfide is known or anticipated, there are very specific requirements to abide by, in accordance with IADC rules and regulations. The reader is advised to consult sources specific to this topic. Shallow gas may be encountered at any time in any region of the world.

The only way to combat this problem if it is encountered is to never shut in the well but rather divert the gas flow through a diverter system, which will hopefully be in place. Shallow gas of high pressure can be encountered at depths as low as a few hundred feet, where the formation fracture gradient is very low. The danger is that if the well is shut in, formation fracturing is more likely to occur, resulting in underground blow, the most severe blowout problem.

Equipment- and Personnel-Related Problems

Equipment

The integrity of drilling equipment and its maintenance are major factors in the minimization of drilling problems. Proper rig hydraulics (pump power) are needed for efficient bottom and annular hole cleaning; proper hoisting power is required for efficient tripping out; proper derrick design loads and drilling-line tension load will allow safe overpull in case of sticking problems; a proper well control system (ram preventers, annular preventers, internal preventers) will allow kick control under any kick situation; a proper monitoring and recording system will allow the monitoring of trend changes in all drilling parameters and will facilitate the accessibility of drilling data for retrieval at a future date for learning; proper tubular hardware should be specifically suited to accommodate all anticipated drilling conditions; and finally, effective mud handling and maintenance equipment will ensure the mud properties fit their intended functions.