

UNDERBALANCED DRILLING: A RESERVOIR DESIGN PERSPECTIVE

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Abstract

Underbalanced drilling is used with increasing frequency on a worldwide basis to reduce invasive formation damage effects and drilling problems associated with many horizontal wells in challenging reservoir exploitation situations. When the primary objective of the underbalanced drilling operation is to reduce or eliminate formation damage effects, the importance of maintaining a continuous underbalanced pressure condition during the complete operation is essential in obtaining the maximum benefit with respect to formation damage reduction. The importance of this has been emphasized in previous work, but this paper details some of the specific reservoir design and operational parameters which must be considered to ensure that the underbalanced pressure condition is maintained on a continuous basis. This includes such issues as pipe connection effects, various wellbore geometries, frictional flow and back pressure effects, localized depletion effects, gravity invasion and drainage effects, countercurrent imbibition effects, hole cleaning, bit jetting, and a number of other issues which can affect the ability to maintain a continuously underbalanced condition in a given reservoir

situation. Examples of these situations will be presented, along with suggestions in certain operational circumstances which can be utilized to reduce the effect of these problems.

What is Underbalanced Drilling?

Underbalanced drilling, in its simplest definition, refers to a condition where the net pressure exerted by the circulating drilling fluid in the annular space between the drill string and the formation is less than the effective pore pressure in the formation adjacent to the wellbore. This results in a pressure imbalance situation where the flow of oil, water, or gas (which may be contained within the pore space) is induced into the wellbore and returns to the surface along with the circulating drilling fluid. Ideally, this condition is generated in every portion of the exposed viable reservoir pay during the complete drilling operation, but in some situations, due to circumstances which will be discussed in detail later in this paper, this may not be the case.

What are the Benefits of Underbalanced Drilling?

Operators who are implementing underbalanced drilling technology in both horizontal and vertical wells commonly give a number of motivations. The most common motivations for the implementation of an underbalanced drilling operation include:

1. A reduction in invasive formation damage and near wellbore skin effects to obtain higher production rates from a given wellbore and reduce or eliminate the necessity for costly and unnecessary completion and stimulation operations.
2. Significantly increased rates of penetration resulting in a reduction in drilling time and costs in some applications.
3. A reduction in drilling problems such as lost circulation, high torque and drag, differential sticking, etc.
4. Instantaneous indication while drilling of the presence of productive intervals and the ability to flow test well drilling.
5. Flush production of reservoir fluids during the drilling operation.

The specific motivation for an underbalanced drilling operation highly influences the importance of maintaining the underbalanced pressure condition on a continuous basis. In most situations, to justify the added expense of using underbalanced drilling technology, the primary motivation is to reduce formation damage to obtain improved production rates of oil or gas from a particular formation. As will be illustrated in greater detail later in the paper, it is in this particular situation in which the continuous maintenance of the underbalanced pressure condition becomes the most essential parameter to be considered. The benefits and disadvantages of underbalanced drilling have been discussed by a number of different authors⁽¹⁻¹⁰⁾.

Types of Underbalanced Drilling Operations

As defined previously, an underbalanced condition is generated at any point in the wellbore where the pressure of the circulating drilling fluid is less than the existing pore pressure in the adjacent formation. This condition can be generated in a number of fashions depending on the specific

reservoir geometry and, more importantly, on the naturally occurring reservoir pressure which is present. In normally pressured formations or overpressured formations, the underbalanced pressure condition may be generated by using either conventionally weighted water-based fluids or low density oil-based drilling fluids. A condition in which the underbalanced condition can be naturally generated, without the need to artificially reduce the density of the circulating drilling fluid beyond its natural single phase condition, is referred to as flow drilling and has been commonly used for many years in areas such as the Austin Chalk in Texas.

In situations where subnormally pressured formations are under consideration, or if a mature reservoir development application is occurring and the reservoir pressure in the target zone has been substantially depleted from its original value, it becomes impossible to obtain an underbalanced condition using normally weighted water-based or hydrocarbon based single phase drilling fluids, due to the weight of the hydrostatic column of fluid above the formation. In such situations, the density of the circulating drilling fluid is further reduced by the inclusion of a non-condensable gas phase, such as nitrogen or natural gas, to reduce the overall circulating fluid density to the point where the hydrostatic head is low enough that an underbalanced pressure condition can be effectively generated in the bottomhole annular space. This type of underbalanced drilling is sometimes referred to as induced or artificial underbalanced drilling, and represents the major topic of discussion of this paper as it represents one of the more challenging applications of this particular technology type. A simplified schematic illustration of a typical induced closed loop underbalanced drilling operation is illustrated as Figure 1.

Common Formation Damage Mechanisms in Conventional Overbalanced Drilling Operations

Formation damage refers to any reduction in the natural inherent permeability of an oil or gas bearing formation due to the invasion or other interaction of produced or injected foreign fluids and solids⁽¹³⁻¹⁵⁾. Certain types of formation damage may also be inherent in associated changes in the temperature; pressure or composition of fluids contained in-situ in the reservoir during production and/or injection operations. The most common types of formation damage occurring during normal overbalanced drilling operations, which an operator would want to avoid through the use of

underbalanced drilling technology, include the following:

1. The motion of in-situ fines and particulates within the pore system caused by high spurt losses of overbalanced water-based or oil-based drilling fluids into the formation⁽¹²⁾.
2. The invasion and permanent entrainment of various types of suspended particulate matter which are commonly contained in overbalanced drilling fluids, including various types of weighting agents, fluid loss agents, bridging agents, as well as naturally occurring drill solids generated by the milling action of the drill bit on the formation.
3. Drill string and drill bit induced near wellbore damage effects such as glazing and mashing.
4. Adverse relative permeability effects such as water blocking and hydrocarbon trapping associated with the invasion and permanent or transient increase in fluid saturations in the near wellbore region^(24,25).
5. Adverse rock-fluid interactions such as swelling clays or deflocculation and dispersion of in-situ clays caused by incompatibilities between invading water-based filtrates.
6. Adverse fluid-fluid interactions which may occur between invading the fluid filtrates and in-situ formation fluids. These would include such phenomena as the formation of various types of scales, precipitates, sludges and emulsions. The precipitation of asphaltenes, hydrates, and paraffins would also fall under this category.
7. Near wellbore wettability alterations which may cause an alteration in the water-oil or gas-oil relative permeability character of the near wellbore region.
8. The invasion of viable bacteria which may cause a subsequent polymer secretion and blocking, corrosion problems, or the generation of toxic hydrogen sulfide gases by sulfate reduction.

In general, underbalanced drilling is considered a technique to avoid the introduction of external fluids and solids into the formation. With the exception, of glazing and mashing, it can be seen that all of the previously discussed formation damage mechanisms are associated with the invasion and entrainment of an extraneous fluid and/or solid into the near wellbore region which causes a resulting

reduction in permeability. The attraction of underbalanced drilling is that, if properly applied and executed, since the net pressure differential is from the formation into the wellbore, the invasion of fluids and solids is naturally minimized or eliminated. If the underbalanced condition is not maintained on a continuous basis, significant invasive formation damage effects may still be present and, in some situations, may actually be amplified in an improperly designed and executed underbalanced drilling operation.

Problems Associated with a Loss of the Underbalanced Pressure Condition

The importance of maintaining a continuous underbalanced pressure condition depends on the primary motivation for underbalanced drilling in the given reservoir situation. If the primary objective is the minimization of drilling problems such as lost circulation or differential sticking, or to significantly increase rates of penetration, periodic incidents of overbalance pressure may not be of significant consequence. If the primary objective for the implementation of underbalanced technology, however, is to reduce formation damage, the overall benefit of the underbalanced operation may be compromised by a relatively short period of overbalance pressure. This phenomena has been discussed at length in the literature^(17,21,22,23) and is pictorially illustrated in Figures 2 to 5, which sequentially represent a poorly designed overbalanced drilling operation (Figure 2), a well-designed overbalanced drilling operation (Figure 3), a well-designed underbalanced drilling operation (Figure 4), and a poorly designed and executed underbalanced drilling operation undergoing periodic pulses of overbalance pressure (Figure 5).

Examination of these figures indicates that conventional overbalanced drilling operations where high fluid losses and invasion occur may result in significant near wellbore damage to the matrix and macro porosity system that exists in the near wellbore region (which may consist of interconnected fractures or vugs) (Figure 2). The objective of a well-designed and executed overbalanced drilling operation is to have the proper fluid rheology and design, which may include certain types of granular or particulate bridging agents, so that a stable and thin filter cake is rapidly generated on the face of a formation which acts as a permanent, impermeable, barrier to prevent the subsequent invasion of damaging filtrate and solids any significant

distance into the productive formation. If this filter cake is properly designed and formed, it can be readily removed by simple mechanical back flow of the formation, or by a very localized chemical or mechanical stimulation and completion treatments (Figure 3). Low fluid loss bridging systems can be designed for overbalanced operations for many different types of reservoir systems; however, obtaining low fluid loss and invasion becomes more challenging in an overbalanced situation in very heterogeneous reservoirs which may contain wide pore throat size distributions, fractures, vuggy porosity, extremely high permeability, or in more homogeneous formations under conditions of very high overbalance pressure. These may all represent situations in which underbalanced drilling may be an attractive option to the operator for the purposes of formation damage reduction. It can be seen that the well-designed and implemented underbalanced drilling operation (Figure 4) eliminates the majority of the concerns associated with fluid and solids invasion. Since the net imposed differential pressure gradient is from the formation into the wellbore, this obviates the majority of the propensity for the potential invasion of the damaging fluid filtrates and solids into the formation (with the exception of certain countercurrent imbibition effects which will be discussed later in the paper). Unfortunately, it can also be seen (Figure 5) that if the underbalanced pressure condition is compromised during the drilling operations, because no stable sealing filter cake has been established on the face of a formation, that rapid invasion of the circulating drilling fluid into the matrix or macro porosity features in the pore system adjacent to the wellbore can occur, even during a relatively brief period of applied overbalance pressure. This phenomena, in general, is further aggravated by the fact that the majority of base fluids used in underbalanced drilling operations have a very low viscosity and generally consist of clear brines or low viscosity oils. These low viscosity fluids are utilized so that turbulent flow can be maintained in the annular space for hole cleaning purposes and to allow for easier disengagement of the multiphase flow and, gas, liquid mixture at the surface in the separator facilities for solids control and liquid recycling purposes. This means that base drilling fluid, if the underbalanced pressure condition is compromised, has little or no apparent rheology and low viscosity in comparison to a conventional drilling mud which is specifically designed with viscosity and fluid loss characteristics in mind. This, therefore, compounds the degree and speed of invasion which may be expected to occur during an overbalanced incident when a typical

underbalanced drilling base fluid is present in the annular region.

Figures 6, 7, and 8 illustrate an additional effect associated with the pressure surging of wells which are undergoing periodic oscillation between conditions of underbalance and overbalance pressure. It can be seen from the examination of these figures that, during each overbalance pressure incident, a partial filter cake may be established subsequent to the overbalanced pulse. (Solids will always be present in such a situation due to the milling action of the drill bit and the relatively poor hole cleaning capability of many underbalanced drilling operations.) When the underbalanced condition is re-established, all or a portion of this filter cake made be removed from the formation face, leaving some residual damage or an undamaged but still unprotected formation face (if we are fortunate) with a halo of filtrate loss. Therefore, subsequent overbalanced pulses must re-establish the partial filter cake, which may result in compound damage and multiple successive incidents of high primary initial filtrate spurt loss repeated each time the underbalanced to overbalance pressure cycling occurs. This is in contrast to a well-designed conventional overbalanced drilling operation where the mud rheology is designed specifically to initially establish a stable and sealing filter cake, which is maintained by the continuous overbalance pressure gradient, and minimizes long-term losses of fluid and solids to the formation on a permanent basis during drilling operations.

Common Modes of Executing an Underbalanced Drilling Operation

Underbalanced drilling can be executed in a number of ways. A detailed discussion of the equipment and specific methodologies used to execute underbalanced drilling operations is beyond the scope of this paper and the reader is referred to the literature^(18,19,20,26) for a more detailed discussion of various underbalanced technologies associated with conventional jointed pipe and coiled tubing drilling operations, surface control equipment, and novel applications such as parasite string injection and concentric string injection technologies.

The vast majority of wells currently being drilled underbalanced still utilize conventional jointed pipe technology with drill string injection of the base drilling fluid and non-condensable gas. This is generally due to the benefit

of lower cost and availability of conventional drilling technology, and the generally superior steering and outreach capability of jointed pipe for extended horizontal well applications in comparison to coiled tubing. A variety of measurement while drilling technologies are utilized with the most common methodology currently being electromagnetic tools (where depth and reservoir conditions permit).

Common Causes of a Loss in the Continuous Underbalanced Pressure Condition

It can be seen in an artificially induced underbalanced drilling situation that the maintenance of the underbalanced pressure condition is much more complex than in a conventional flow drilling situation where, even if circulation ceases and a full hydrostatic column of the drilling fluid is applied to the formation, the underbalanced pressure condition is still maintained. A number of common sources of oscillation in the bottomhole pressure are observed during artificially induced underbalanced drilling operations, these include:

Increases in Mud Weight

During normal drilling operations, mud weight often increases due to the milling action of the drill bit on the formation and the inability of the surface solids control equipment to adequately remove these solids (particularly drill solids <10 microns in diameter). Documented cases exist during drilling operations, particularly with hydrocarbon based fluids, where increases in mud density over an extended lateral section in excess of 500 kg/m³ have been documented (solely due to natural solids accumulation). This obviously will increase the effective bottomhole pressure and may make maintenance of an underbalanced pressure condition, even in a classic flow drilling application, difficult or impossible. Therefore accurate monitoring of the mud weight and factoring of this into the flow calculations for computation of effective bottomhole circulating pressure on a continuous basis is essential for the proper evaluation and monitoring of the underbalance pressure condition.

Pipe Connections in Jointed Pipe Drilling Operations

Pipe connections represent some of the most significant potential bottomhole pressure oscillations when using jointed pipe technology for underbalanced drilling. In the majority

of these operations, concurrent injection of the base drilling fluid and non-condensable gas occurs through the drill string. Obviously, this necessitates the termination of injection whenever the drill string must be broken to make a pipe connection. The periodic flow disturbances caused by the cessation of gas and fluid injection result in a potential oscillation of the bottomhole pressure. This phenomena is schematically illustrated in Figures 9 to 11. It can be seen upon cessation of flow associated with the connection that annular fluid velocity decreases and the frictional back pressure component associated with the motion of the fluid from downhole to the surface is reduced. This results in an effective reduction in the bottomhole pressure. If the reservoir under consideration is producing hydrocarbon liquids or water, it may result in an increased inflow of these fluids into the wellbore (in addition to those already entering due to the underbalanced pressure condition). These fluids entering the wellbore and horizontal section may commingle with additional fluids which may fall back from the annular vertical section of the wellbore if the connection period is long enough that sufficient velocity cannot be maintained to continue to entrain and lift slugs of liquid. This ultimately results in the potential accumulation of a volume of dense phase liquids in the horizontal section of the wellbore or the base of the vertical section (if a vertical well is under consideration). When the connection is complete and flow resumes, this slug of fluid is subsequently circulated into the vertical annular section of the wellbore where a large hydrostatic back pressure may have to be applied to lift the fluid column vertically to the surface. This may result in sufficient backpressure being applied to the formation during this period to cause a condition of overbalance pressure to be generated as is schematically illustrated in Figure 11.

This is one reason real-time bottomhole pressure measurement during an underbalanced drilling operation is considered essential, as it allows the operator the ability to adjust operations 'on-the-fly' to match current bottomhole pressure conditions to ensure that an underbalanced pressure condition is maintained at all times during the drilling operation.

The effect of pipe connections can be greatly reduced by proper operating practices which includes the use of trained rig crews capable of making connections in a rapid fashion, the appropriate placement of multiple drill string floats to avoid extended periods of time to bleed internal string pressure down to facilitate these rapid connections,

maintaining annular flow during the connection to avoid fluid fall back and to minimize bottomhole low pressure reductions due to an elimination of frictional back pressure effects, and the use of large rigs capable of drilling with double or triple pipe stands to minimize the physical number of connections required.

The use of coiled tubing has distinct advantages for underbalanced drilling as the necessity of connections is obviously eliminated. Some of the advantages of coiled tubing can be obtained with a conventional jointed pipe operation by using special wellbore geometries which incorporate cemented behind casing tubing strings or retrievable concentric casing strings which allow for the continuous injection of non-condensable gas into the vertical annular section, even during pipe connections or other operations. These geometries tend to be technically complex and expensive and are, in many cases, restricted to new drill applications. Therefore, they have not been extensively utilized.

Measurement While Drilling Operations

For the majority of underbalanced drilling operations, some type of measurement while drilling capability is required to monitor both wellbore trajectory for horizontal applications, and to also transmit valuable bottomhole pressure data back to the surface. Classically, many early-underbalanced drilling operations utilized conventional mud pulsed telemetry to transmit MWD data. Since mud pulsed telemetry relies on an incompressible fluid phase to transmit the data back to surface, a compressible gas phase cannot be present in the internal drill string while a survey was being conducted. This results in periodic conditions of full hydrostatic pressure applied to the wellbore for the purposes of survey transmission, which obviously compromises a large portion of the potential advantage of the underbalanced drilling operation. The use of parasite string and concentric string technology allows the use of a conventional mud pulsed telemetry, while still maintaining the underbalanced pressure condition in the majority of the wellbore. Wet connect type steering tools have been utilized in some situations and result in considerable technical difficulty and extended connection times and drilling delay times for steering and orientation purposes.

A technology currently in use for most underbalanced drilling operations is electromagnetic measurement while

drilling tools (EM - MWD) which send and receive survey data through the transmission of an electromagnetic pulse directly through the formation to receivers at surface. Electromagnetic telemetry has proven to be a reliable technology, but has limitations associated with high resistivity formations and does not operate reliably at depths in excess of 2500 meters without special modifications for extended range transmission. Electromagnetic telemetry has also proven to be sensitive to vibration associated with pure gas or air drilling operations which has limited its utility in some applications of this type.

Another advantage of coiled tubing as a drilling option for underbalanced operations is that a continuous internal wireline system can be utilized for relatively trouble free MWD transmission and steering purposes which does not endanger the maintenance of the underbalanced condition.

Tripping Operations-Kill Operations

Obviously, if bit trips or other operations are required which would necessitate the killing of a well that is being drilled underbalanced, the efficacy of the underbalanced operation may be compromised. In general, snubbing operations are utilized in such situations to maintaining the wellbore in a state of continuous underbalanced flow at all times in order to obtain the maximum benefit. Bit life is generally longer in most underbalanced drilling operations in comparison to overbalanced drilling and, in many situations, the potential risk associated with a bit trip may be unjustified if the well is near the desired penetration length and flow rates are acceptable. In general, a new bit and bottomhole PDM assembly is recommended prior to initiating drilling a underbalanced horizontal section to reduce the necessity of a potentially a preventable bit trip and overbalanced incident.

Hole Cleaning/Cuttings Dispersion

The majority of underbalanced drilling operations use low viscosity fluids and rely on highly turbulent circulation rates of the base fluid/gas/produced fluids mixture to transport cuttings back to the surface and maintain the wellbore in a clean condition. Poorly centralized pipe and periodic cessations of flow combined with flow restrictions and hole washouts may result in periodic problems associated with hole cleaning for underbalanced drilling operations. Typically cuttings must be extensively reworked

by string and bit action downhole prior to being transported to the surface in drilling operations of this type, and it is not uncommon to obtain very poor quality desegregated cuttings from underbalanced drilling operations, particularly as gas rates become very high and 'air' drilling conditions are approached. Poor hole cleaning results in the possible formation of mud rings which may contribute to high torque and drag as well as significant annular flow restrictions which may cause high backpressures. This will result in a condition of potential overbalance pressure being generated behind the flow restriction.

In addition, if the formation matrix has a wettability opposite to that of the base fluid in use for drilling purposes, problems with cuttings dispersion and agglomeration may be present. This is a common occurrence in pure oil-based systems which are sometimes used for underbalanced drilling operations and is schematically illustrated as Figure 12. It can be seen that, as the drill bit mills through a water-wet formation, the water wet sandstone or carbonate cuttings become encapsulated in the external oil phase. If the suspended cuttings still retain their water wet nature, they tend to have a natural affinity to repel the surrounding oil phase and be attracted to other water wet materials, which generally include other cuttings in suspension and the formation face surrounding the annular portion of the wellbore. This can result in the rapid and significant agglomeration of sizable masses of cuttings. For an oil-based system, generally an adequate concentration of oil wetting surfactant (to oil wet the suspended cuttings to ensure that they remain uniformly dispersed and can be readily transported back to surface) addresses the problem (an effect commonly observed for invert mud systems). The use of oil wetting surfactants, while possibly beneficial for hole cleaning in such situations, may be adverse to formation production characteristics if the underbalanced pressure condition is compromised and oil-wetting surfactants are displaced into the formation matrix. This may cause a near wellbore wettability alteration to a more oil wet condition, which may substantially reduce ultimate oil phase productivity and potentially increase the mobility and production rates of any mobile water that may be present in the formation.

Frictional Flow and Back Pressure Effects

Most artificially induced underbalanced drilling operations are associated with high turbulent flow rates in a

restricted annular flow space. This situation is accompanied by the potential for significant frictional backpressure effects both inside the drill string and in the returning annular space which may comprise the horizontal and vertical sections of a well. Obviously, pressure calculations in this situation are extremely complex and are normally evaluated using a variety of recently developed numerical simulators.

Figure 13 provides a simplified illustration of a typical pressure history of a unit volume of given fluid, as it would circulate through the flow path of a typical underbalanced drilling operation. Examination of this figure illustrates the complex combination of frictional flow and hydrostatic flow effects which occur in an underbalanced operation. As fluid moves down the central portion of the drill string in the injection path, in addition to the applied pump pressure to circulate the fluid, pressure increases due to the applied hydrostatic head of the fluid column as the fluid moves deeper into the well. This is partially counteracted by some pressure reductions due to flow restrictions such as drill string floats and associated friction pressure drops in the string itself. Once the fluid transitions into the horizontal section, the hydrostatic head remains constant (if a true horizontal trajectory is obtained) and pressure gradually declines due to frictional flow effects associated with the displacement of the turbulent multiphase flow system through the horizontal portion of the drill string. A large pressure drop is generally encountered across the positive displacement pump assembly to provide the power to run the motor due to orifice restrictions moving through the drill bit. The pressure observed at this particular location as the fluid exits the drill bit is the prime interest for the underbalanced drilling operation as, for a typical wellbore geometry, this represents the position of maximum exposed pressure which the formation will be encountering. Bottomhole real-time pressure while drilling sensors are usually mounted a short distance behind the bottomhole assembly and, in many situations, can provide a reasonable approximation of this maximum pressure. As the fluid moves back towards the surface in the annular flow section, the pressure continues to drop due to frictional back pressure effects associated with the motion of the fluid, solids and produced reservoir fluids through the annular flow space. Once the fluid moves into the vertical annular section, pressure drops quickly due to reduction in hydrostatic head and also a potential reduction in the overall fluid density due to the presence and elution of compressible gas. The amount of back pressure maintained at surface also has an obvious strong shifting effect on the

pressure distribution of the entire flow loop. To maintain a minimum bottomhole pressure, this value is obviously kept as low as possible.

Examination of this profile indicates that an evaluation of bottomhole pressure profile for an underbalanced drilling operation is a complex calculation. The calculation of the effective bottomhole pressure profile is complicated, not only by the complexities of the wellbore geometry, but also by the inflow of formation fluids and the highly compressible nature of the gas charged system under consideration. Therefore, simple numerical predictions coupled with observed surface pressures may be an unreliable technique to use for bottom low-pressure prediction and once again the importance of real-time bottomhole pressure while drilling is reinforced.

The effective bottomhole pressure will also be a specific function of the fluid rheology and type of fluid utilized as well as the length of the wellbore at a given time. Examination of Figure 13 indicates that the magnitude of the frictional backpressure obviously increases with both fluid viscosity and the length of the horizontal section. From this it becomes obvious that for a given wellbore geometry and fluid type and rate regime, there is a maximum horizontal length that one can obtain and still maintain a sufficiently low bottomhole pressure condition at the bit to the underbalanced. This limitation must be carefully evaluated and understood prior to commencing an extended reach horizontal well where underbalanced drilling technology is contemplated.

Figure 14 illustrates the interaction of fluid flow rate and gas rate and its potential effect on bottomhole pressure. For a given wellbore geometry, the bottomhole pressure condition can be controlled either by the frictional backpressure effects or conversely via hydrostatic effects. For a given fluid injection rate, by examining Figure 14, it can be seen that, as gas injection rate is increased, eventually an optimal minimum bottomhole pressure is achieved. As gas rate is increased beyond this point, the density reduction associated with the extra gas being entrained in the overall circulating fluid system is counteracted by the additional frictional back pressure associated with the displacement of the greater overall fluid rate through the circulating flow loop. Therefore, even though gas phase volume is increased, the overall effect is to increase the bottomhole pressure. If an undesirable situation of high bottomhole pressure is

encountered during a UBD operation, it does not necessarily mean that the natural solution is to increase the injected gas rate. This may further exacerbate the problem with the well if operating in the region classified as friction dominated which occurs to the right hand side of the minimum bottomhole pressure point on Figure 14. Normally, most operators prefer to operate at a combination of liquid and gas injection rates, which places the wellbore slightly into the friction-dominated regime. The reason for this rationale (even though higher gas injection rates are required to achieve this condition) is that bottomhole pressure variations (associated with moderate fluctuations in the gas rate in the friction-dominated regime) are relatively moderate in comparison to those in the hydrostatic pressure-dominated regime (which occurs to the left-hand side of the minimum pressure inflection point on Figure 14).

Because some oscillations in gas flow rate tend to be inevitable in most artificially induced underbalanced drilling operations, operating in the frictional dominated pressure regime tends to substantially minimize the associated bottomhole pressure fluctuations in comparison to a situation where one is operating in the much more pressure sensitive hydrostatic dominated regime.

Bit Jetting Action

Figure 15 provides an illustration of potential invasion of drilling mud filtrate and solids due to jetting effects which may occur at the drill bit -formation interface. Although an underbalanced pressure condition may be present in the wellbore and at the bit, high linear and radial fluid velocities (caused by liquid exiting the drill bit and abruptly impacting the formation face) may result in point source velocity stalling and Bernoulli effects (conversion of the kinetic energy of velocity into pressure) and may also result in a localized point of pressure increase on the formation face (which can initiate the intrusion of filtrate and solids into the reservoir in the portion of the formation currently being drilled by the bit). This invasion depth is likely of shallow extent, due to the relatively short exposure time if rates of penetration are reasonable, but may still result in some near wellbore impairment in open hole flow situations (which 99% of underbalanced completions represent).

Localized Depletion Effects

Figures 16 and 17 provide schematic illustrations of the

phenomena of localized depletion and how it may impact fluid invasion in an underbalanced drilling operation. In contrast to a conventional overbalanced drilling procedure, the formation in this case is in a state of flux as drawdown conditions are applied which result in a flow of fluids from the reservoir into the wellbore. This flow condition necessitates a drawdown gradient being present in the reservoir adjacent to the wellbore, and after a period of inflow, well face pressure may approach that of the circulating drilling fluid with a transient gradient extending from the wellbore for a distance corresponding to the drainage radius at which the reservoir pressure is being maintained. The impact of this effect is of significance to sections of the well drilled earlier and exposed to circulating drilling fluid at an underbalanced pressure condition for an extended period of time as the drilling process proceeds. Due to the fact that localized drawdown effects will have resulted in pressure depletion of the near wellbore region in these areas, if any significant increases in circulating fluid pressure occur, this may result in a transient situation where the pressure in the circulating drilling fluid is greater than the adjacent formation pressure (even though the value of the circulating fluid pressure may still be less than the original pressure condition of the reservoir). This could result in some continuing inflow from the reservoir from the non-depleted portions near the drill bit, leading the operator to believe that the wellbore is still in an underbalanced condition (which a portion of it is). This phenomenon is especially problematic in low permeability formations, as steep drawdown gradients will be generated and the ability of the reservoir to rapidly repressure the depleted zone upon a cessation of flow is inherently limited due to the low permeability of the matrix.

Potential Damage Issues That May Occur Even Though Underbalanced Condition is Maintained

The optimum scenario to minimize this problem is to have the degree of underbalance pressure to which a given portion of the formation is exposed gradually increase over time as the well is drilled. This happens naturally to a certain extent due to changes in frictional backpressure effects as the length of the vertical or horizontal section increases. If the pressure remains at a constant value at the bit, as well length increases, by definition, the pressure and proceeding point in the wellbore will be less than this value due to simple frictional head effects required to displace the fluid down the annular section. Due to the fact that certain pressure oscillations are inevitable in normal underbalanced drilling operations, design protocol suggests, if possible, that a condition of gradually increasing underbalance pressure

should be maintained throughout drilling operations to ensure that every portion of the reservoir exposed to the circulating drilling fluid has the opportunity to be in a condition of gradually increasing drawdown pressure.

Gravity Drainage Effects

A common application for underbalanced drilling is in highly fractured or vugular carbonates or highly pressure depleted formations where significant problems with lost circulation of drilling fluids make drilling difficult or impossible. Although underbalanced drilling in many situations represents a solution to this problem, reservoirs containing cavernous vugular porosity or massive open fractures, at significantly pressure depleted levels, may still represent the opportunity to sustain significant losses of fluid, even if an underbalanced situation is continually maintained, which may make circulation impossible. This phenomena is illustrated as Figure 18. Examination of Figure 18 illustrates that gravity induced drainage into macroporous media will occur on the lower side of a deviated or horizontal well if the orifice velocity caused by exiting gas or oil is insufficient to counteract the gravitational influx effect of the circulating drilling fluid. If the fracture or vug aperture is too large, or the pressure differential between the circulating drilling fluid and the reservoir is too small to sustain sufficient velocity, significant gravity segregation and drainage of the water or oil based drilling fluid downwards into the macro porosity system can occur, which may still result in a situation of catastrophic lost circulation even though an underbalanced and flowing well condition is being maintained.

Certain formations may still be susceptible to certain damage effects, even if an underbalanced pressure condition is maintained during the drilling operation. Damage mechanisms which are most prevalent in this particular category are countercurrent imbibition of fluids and glazing and mashing effects.

Countercurrent Imbibition

Figure 19 provides a pictorial illustration of the mechanism of countercurrent imbibition during underbalanced drilling. This damage mechanism is unique to the application of underbalanced drilling to formations

which exhibit subirreducible initial wetting phase saturations of the same phase in use as the base fluid for the drilling operation. The most common occurrence of this is in low permeability gas reservoirs which have been subjected to desiccation effects, resulting in the unusual combination of low permeability reservoir pay and abnormally low initial water saturation (i.e. less than would be expected for a normal capillary desaturation at the equivalent column high present in the reservoir for rock of that permeability). Detailed discussions of reservoirs of this type are contained in the literature^(24,25). Countercurrent imbibition effects are motivated by an extremely adverse capillary gradient which exists between the formation and the circulating the wetting phase fluid. Formations existing at subirreducible saturations represent a condition of extreme potential energy to wetting phase uptake or imbibition (generally water in this situation). Direct exposure of the surface of a formation in this condition to the wetting fluid (for example the use of the water-based drilling fluid in a low permeability, low initial water saturation gas reservoir situation) will result in the preferential uptake or 'wicking' of a portion of the circulating water-based fluid into the formation in the near wellbore region until a equilibrium saturation condition to counteract the underbalance pressure currently present at that point is obtained. Since capillary pressure curves become asymptotically high at low initial water saturations, capillary imbibition has been demonstrated to counteract underbalance pressure gradients which may exceed thousands of psi. The overall results of this process is the gradual imbibition of an elevated water saturation into the near wellbore region, which may have significantly adverse relative permeability effects upon subsequent production of gas from the wellbore. Detailed experimental verification and discussion of this phenomena is contained in the literature^(16,17).

In cases where countercurrent imbibition is known to be a potentially significant problem, the fluid base used for the underbalanced drilling operation in general should not be the wetting fluid of the formation (i.e.-a water-based drilling fluid in a low permeability gas reservoir which is known to exhibit water-based phase trapping effects and a subirreducible initial water saturation). Possible alternatives would be to avoid the use of a conventional fluid base system altogether (pure gas drilling), or possibly consider the use of a non-wetting hydrocarbon based drilling fluid, such as diesel or reformat, which does not exhibit natural spontaneous capillary imbibition into the matrix.

Glazing and Mashing

Figure 20 provides an illustration of near wellbore glazing and mashing effects. Glazing and mashing refers to extremely shallow localized damage which is caused by direct bit action or interaction between sliding and rotating drill string and the formation. These phenomena can occur even during underbalanced drilling operations, and in some cases may be exacerbated by underbalanced drilling due to poor hole cleaning effects and a higher concentration of available drill cuttings and solids in the wellbore.

Glazing refers to interactions between the drill bit and the formation, and is generally problematic primarily for pure gas drilling applications due to the poor heat transfer capacity of pure gas systems (in comparison to liquids) which results in high temperatures being generated at the rock-drill bit interface. The combination of high temperature, minute amounts of connate water, and drill cuttings is believed to create a very thin but low permeability glaze directly on the face of the wellbore which is very similar in character to that observed on fired ceramic pottery. This glaze, although extremely shallow, can substantially impaired production in an open hole completion situation (which is common for underbalanced wellbores).

Mashing effects are believed to be related to the action of poorly centralized rotating and sliding drill string interacting with cuttings in the wellbore as drilling occurs and results in the continual working of these fines and cuttings in a polishing action into the wellbore face. Once again, this damage is of extremely shallow extent and is inconsequential in a perforated or fractured completion, but may represent a substantial barrier to inflow in an open hole scenario.

Although glazing and mashing are difficult phenomena to physically duplicate in a laboratory environment, the effect can clearly be seen on air drilled core samples and sidewall core samples obtained from air drilled open hole completions where actual samples of the wellbore-formation interface can be obtained for direct microscopic examination.

Conclusions

This paper illustrates that underbalanced drilling can be a very beneficial process in certain reservoir situations for the purpose of reducing formation damage, if properly

designed and executed. Multiple potential pitfalls exist in the design of underbalanced drilling operations which may compromise the ability to maintain a properly underbalanced condition throughout the drilling (and completion) operation. While some formations are relatively forgiving to a limited number of overbalance pressure incidents, in virtually all situations it can be demonstrated that moderate to severe reductions in productivity will occur during multiple overbalanced incidents and in order to maximize the ultimate well productivity, proper design is essential. It can be seen that inappropriate execution of an underbalanced drilling job can, in certain situations, result in even poorer well performance than if the well has been drilled in similar circumstances with a well-designed and executed conventional overbalanced operational approach.

Acknowledgments

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References

1. DOANE, R.D. et al, "Successful Drilling of an Underbalanced Horizontal Well in the Rigel Halfway Pool - Laboratory Screening and Field Results", Paper presented at the International Conference on Horizontal Well Technology, Calgary, Alberta, Canada, Nov. 18-20, 1996
2. CHURCHER, P.L. et al, "Designing and Field Testing of Underbalanced Drilling Fluids to Limit Formation Damage: Examples from the Westrose Field, Canada".
3. COOPER, S.C. et al, "Horizontal Underbalanced Wells Yield High Rates in Colombia", *World Oil*, Sept. 1998, 75.
4. ELROD, J.P., "Horizontal Air Drilling Increases Gas Recovery in Depleted Zones", *Oil and Gas Journal*, June 30, 1997, 49.
5. MCGREGOR, B. et al, "Productivity Improvements in a Deep Underground Tight Gas Reservoir Through the Application of Horizontal Underbalanced Drilling", Presented at the 3rd International Underbalanced Drilling Conference, The Hague, Netherlands, Oct. 1991.
6. DEIS, P. et al, "Infill Drilling in the Mississippian Midale Beds of the Weyburn Field Using Underbalanced Horizontal Drilling Techniques", CADOC 93-1105, presented at the CADE/CADOC Spring Drilling Conference, April 14-16, 1993, Calgary, Canada.
7. DEIS, P. et al, "Development of an Underbalanced Drilling Process: An Operators Experience in Western Canada", presented at the 2nd International Conference on Underbalanced Drilling, The Hague, Netherlands, Oct. 1995.
8. URKIW, F.J. et al, "Optimization of Underbalanced Drilling Operations to Improve Well Productivity", CIM 96-74, presented at the 47th ATM of the Petroleum Society of CIM, Calgary, Canada, Jan. 10-12, 1996.
9. LUNAN, B., "Surface Control Systems for Underbalanced Drilling", *JCPT*, Sept. 1995.
10. SAPONJA, J. et al, "Considerations for Underbalanced Drilling with Jointed Pipe", Paper presented at the First International Underbalanced Drilling Conference and Exhibition, The Hague, Netherlands, Oct. 2-4, 1995.
11. BENNION, D.B., LUNAN, B., SAPONJA, J. "Underbalanced Drilling and Completion Operations to Minimize Formation Damage: Reservoir Screening Criteria for Optimum Application", Paper presented at the 47th Annual Technical Meeting of the Petroleum Society of CIM, Calgary, Alberta, June 10-12, 1996.
12. ENG, J.H. et al, "Velocity Profiles in Perforated Completions", *JCPT*, Oct. 1993, Volume 32, No.8.
13. BEATTY, T. et al, "Minimizing Formation Damage in Horizontal Wells: Laboratory and Field Case Studies", Paper presented at the CIM 1993 Annual Technical Conference, Calgary, Alberta, May 9-12, 1993.
14. BENNION, D.B., THOMAS, F.B., BENNION, D.W., BIETZ, R.F., "Formation Damage Control and Research in Horizontal Wells", Paper presented at the 5th International Conference on Horizontal Well Technology, Houston, TX, Nov. 9-11, 1993.
15. BENNION, D.B., THOMAS, F.B., BIETZ, R.F., JAMALUDDIN, A.K.M., "Recent Investigations Into Formation Damage and Remediation Technology for

- Horizontal Well Applications”, Paper presented at the 9th International Conference on Horizontal Well technology and Applications, Houston, TX, Aug. 25-27, 1997.
16. BENNION, D.B., THOMAS, F.B., “Underbalanced Drilling of Horizontal Wells: Does It Really Eliminate Formation Damage?”, Paper presented at the SPE Intl. Symposium on Formation Damage Control, Lafayette, LA, Feb. 7-10, 1994.
 17. BENNION, D.B., THOMAS, F.B., BIETZ, R.F., BENNION, D.W., “Underbalanced Drilling, Praises and Perils: Lab and Field Experience”, Paper presented at the 5th Annual Conference on Horizontal Well Technology, Calgary, AB, Nov. 21, 1995.
 18. BENNION, D.B., THOMAS, F.B., BIETZ, R.F., JAMALUDDIN, A.K.M., “Coiled Tubing - The Future of Underbalanced Drilling?”, Paper presented at the 5th International Conference on Coiled Tubing Technologies, Dallas, TX, Jan. 8-10, 1997.
 19. BENNION, D.B., “UBD with CT has Pluses, Minuses”, *Special Report: Coiled Tubing, Slim Hole and Short Radius*, January 1998, 113.
 20. TIECHROB, R, et al, "Use of a Concentric Drill String System for Underbalanced Completion", Oil and Gas Journal, 1994.
 21. BENNION, D.B., "Underbalanced Drilling Offers Pluses and Minuses - Part I", Oil and Gas Journal, January 2, 1996.
 22. BENNION, D.B., "Underbalanced Drilling Offers Pluses and Minuses - Part II", Oil and Gas Journal, January 9, 1996.
 23. BENNION, D.B., "Underbalanced Drilling, Praises and Perils", SPE 35242, Presented at the SPE Permian Basin Oil and Gas Recovery Conference, March 27-29, 1996, Midland, Texas.
 24. BENNION, D.B., et al, "Water and Hydrocarbon Phase Trapping in Porous Media - Diagnosis, Prevention and Treatment", Paper CIM 95-69 Presented at the 46th Annual Technical Meeting of the Petroleum Society of CIM, May 14-17, 1995, Banff, Canada.
 25. BENNION, D.B., et al, "Reductions in the Productivity of Oil and Low Permeability Gas Reservoirs Due to Aqueous Phase Trapping", Journal of Canadian Petroleum Technology, November, 1994.
 26. MEHTA, et al, "Flash Tests to Determine Combustible Limits for Underbalanced Drilling", Paper presented at the UNITAR Conference, Houston, Texas, February, 1995.

Figure 1 - Typical "closed system" UBD Operation

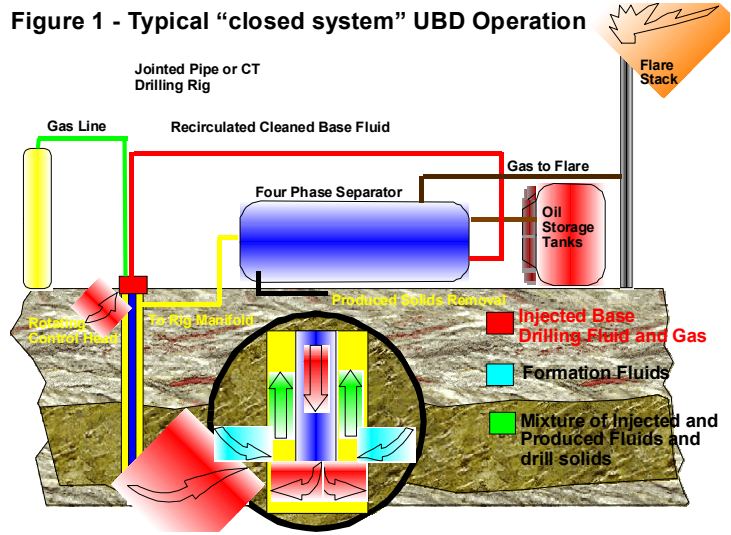


Figure 2 - Poorly Designed Overbalanced Drilling Operation

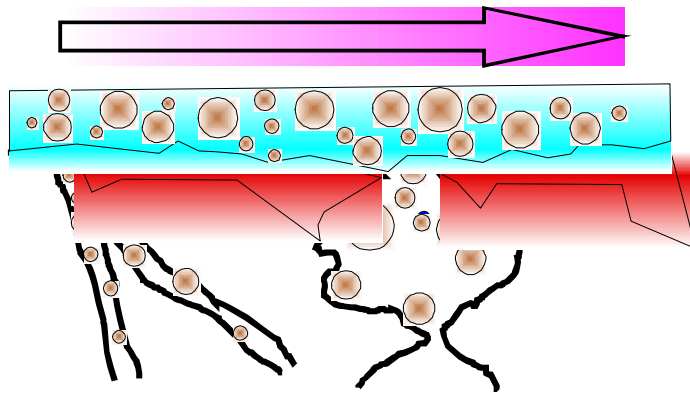


Figure 3 - Well Designed Overbalanced Drilling Operation

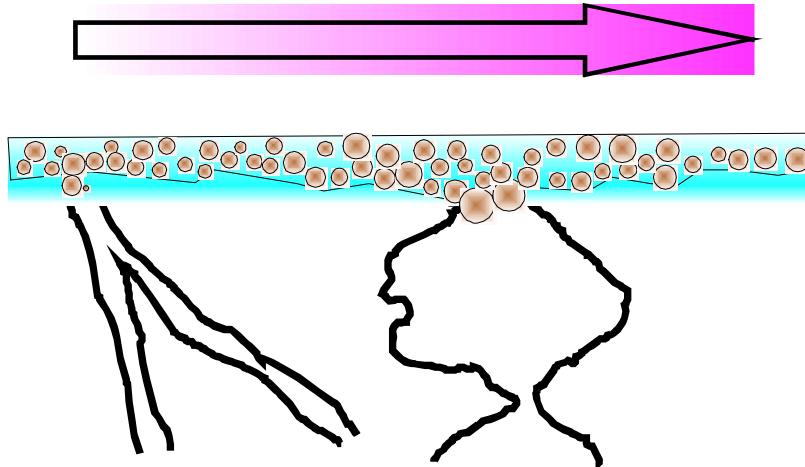


Figure 4 - Well Designed Underbalanced Drilling Operation

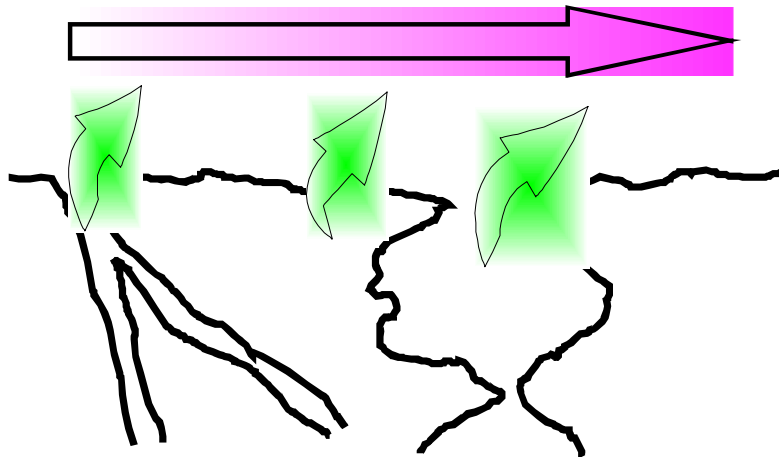


Figure 5 - Poorly Designed Underbalanced Operation Experiencing an Overbalanced Pulse

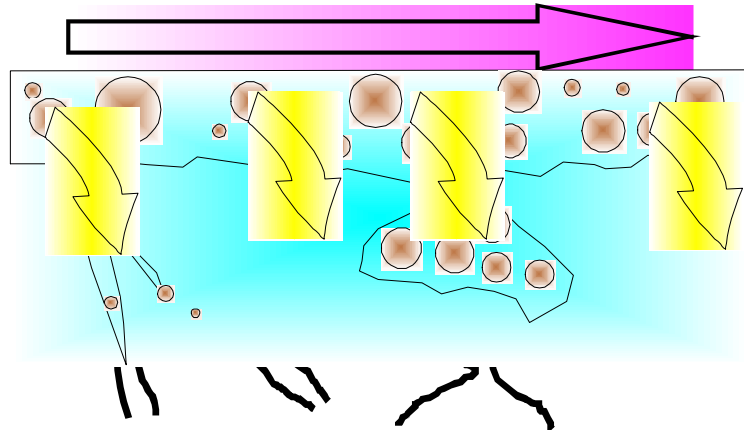


Figure 6 - Invasion of Filtrate and Solids During First Overbalanced Incident

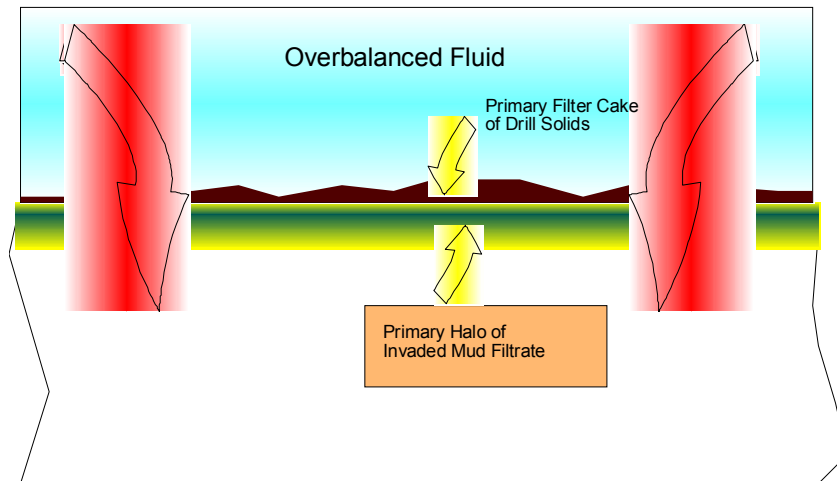


Figure 7 - Partial Removal of Filtrate and Solids During Resumption of UB Operations

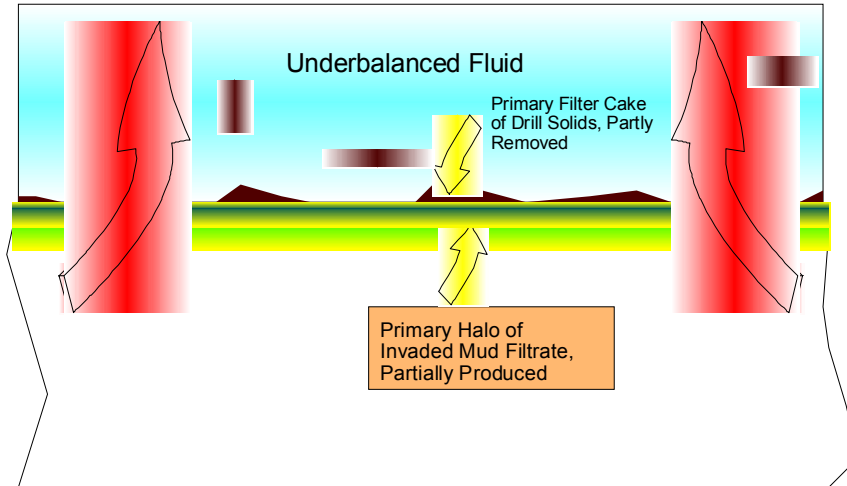


Figure 8 - Invasion of Filtrate and Solids During Next Overbalanced Incident

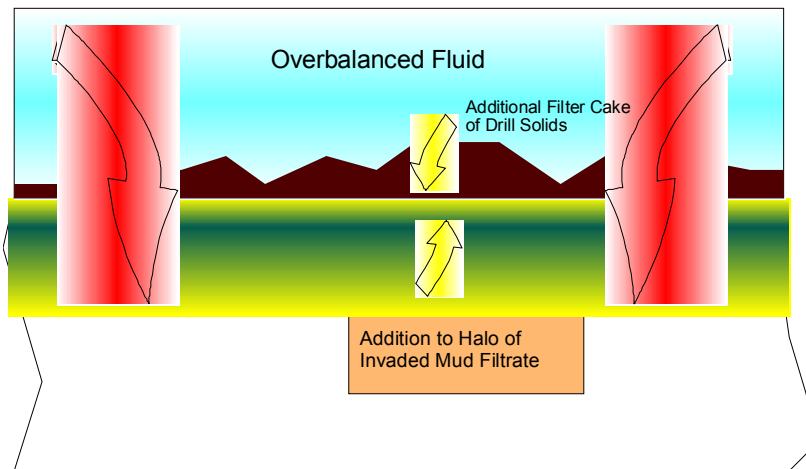


Figure 9 - BHP Prior to a Pipe Connection

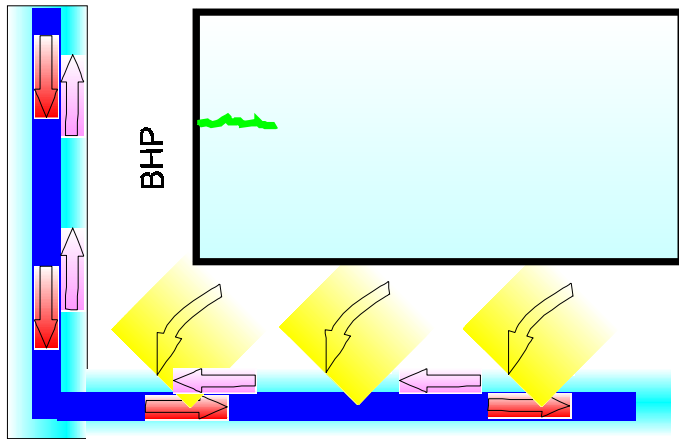


Figure 10 - BHP During a Pipe Connection

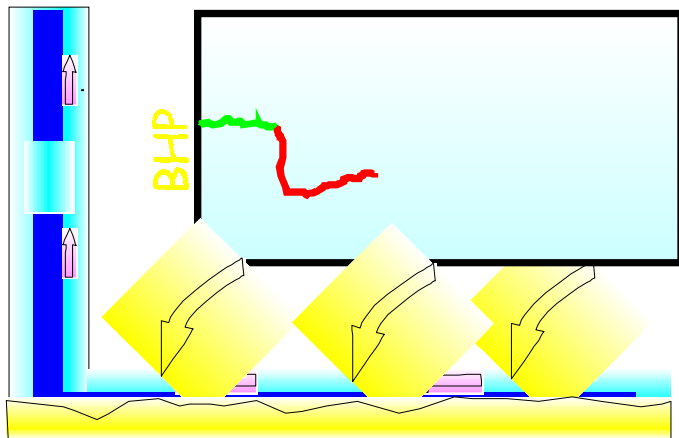


Figure 11 - BHP After a Pipe Connection

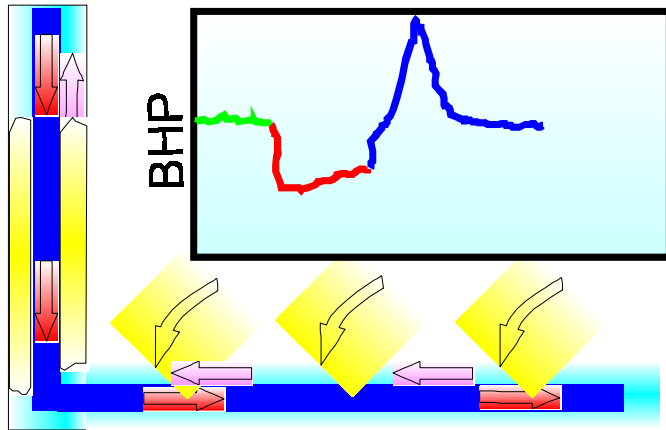
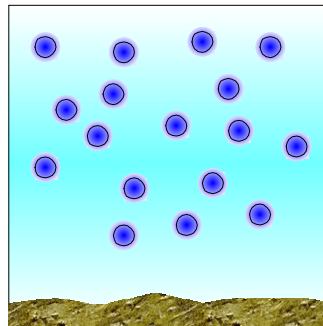
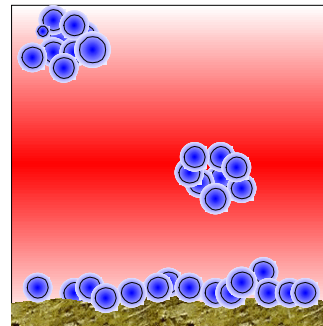


Figure 12 - Illustration of Wettability Induced Cuttings Dispersion/Agglomeration



Water Wet Cuttings Well Dispersed in Water Based Fluid



Water Wet Cuttings Well Dispersed in Oil Based Fluid

Figure 13 - Typical Flow Loop Pressure Profile for a UBD Operation

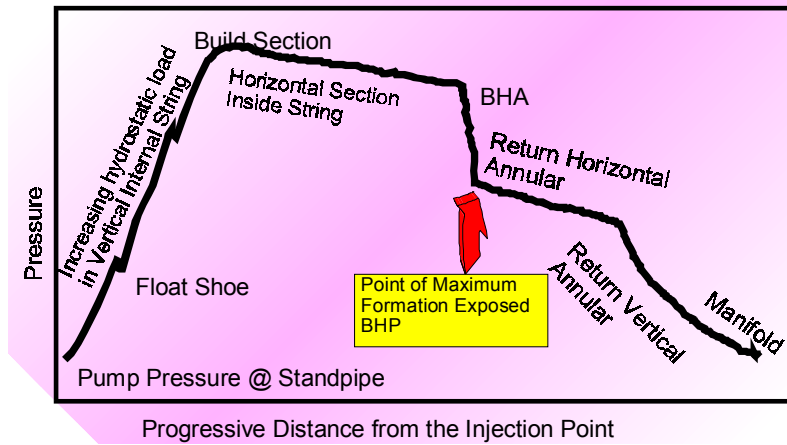


Figure 14 - Interrelation Between Gas Flow Rate and BHP

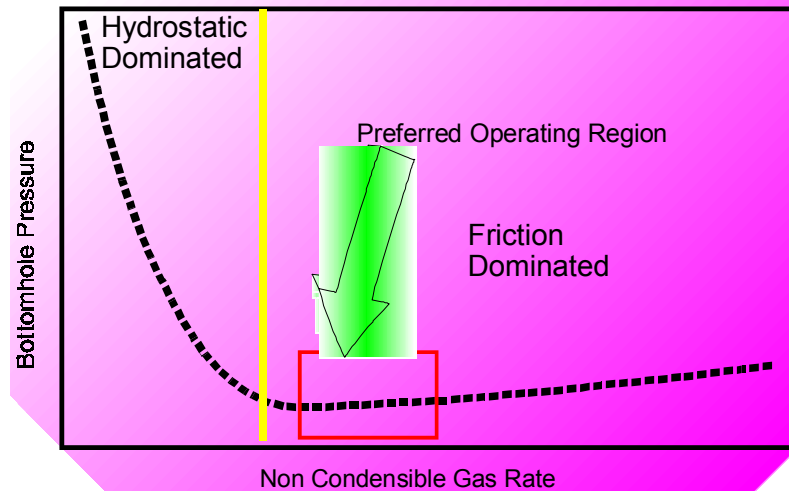


Figure 15 - Bit Jetting Effects

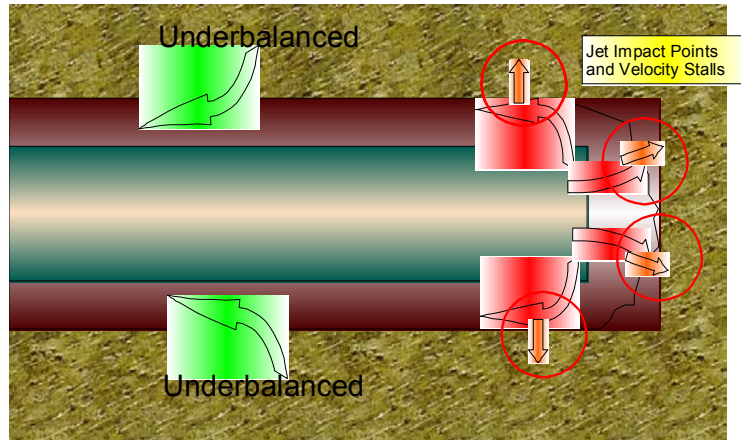


Figure 16 - Illustration of Localized Depletion Effects, Prior to BHP Increase

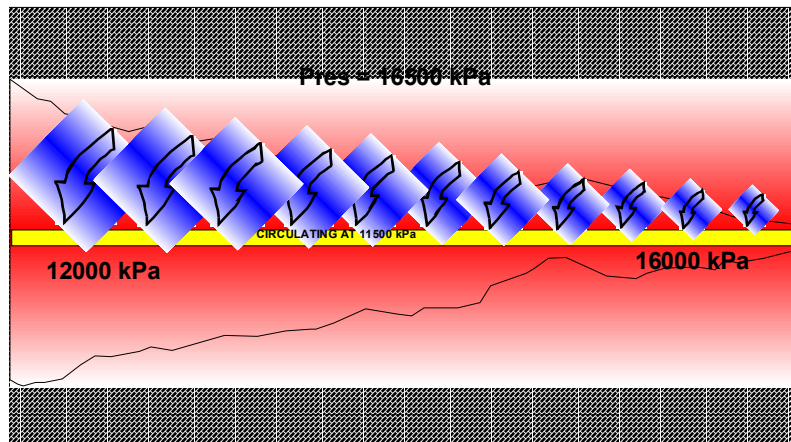


Figure 17 - Illustration of Localized Depletion Effects, After BHP Increase

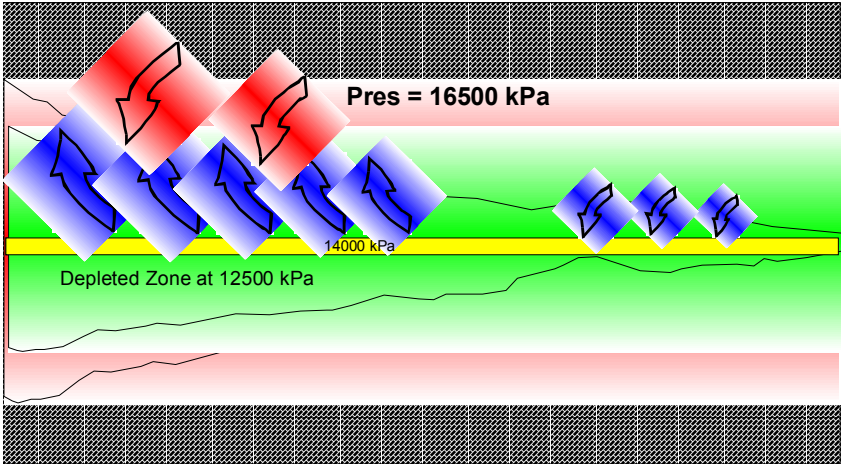


Figure 18 - Gravity Drainage in Macroporosity

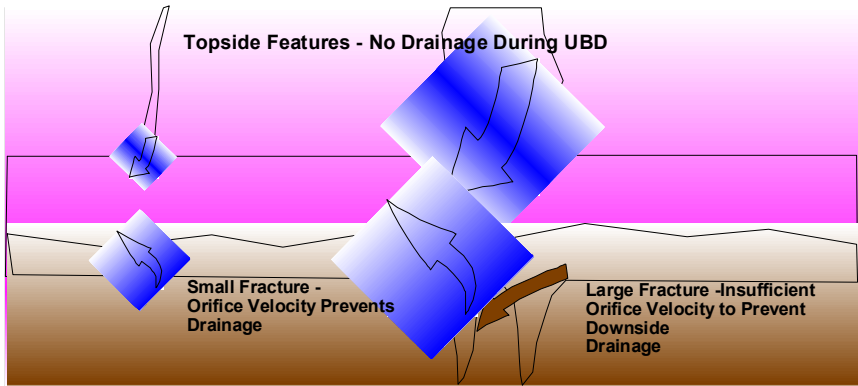


Figure 19 - Illustration of Countercurrent Imbibition Effects

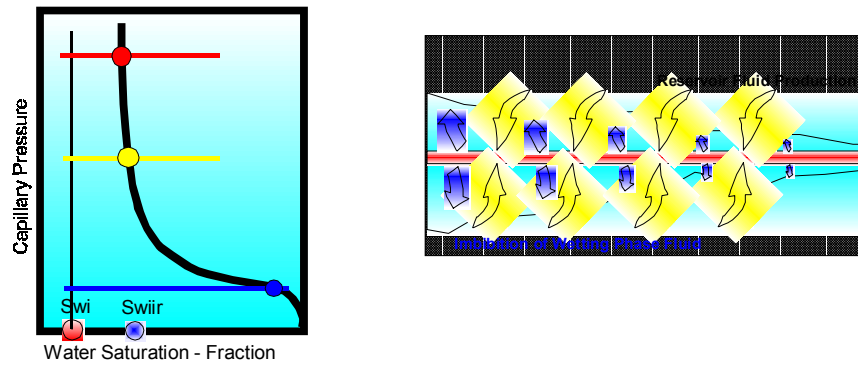


Figure 20 - Glazing and Mashing Effects

