Summary

Underbalanced drilling (UBD) has been used with increasing frequency to minimize problems associated with invasive formation damage, which often greatly reduce the productivity of oil and gas reservoirs, particularly in openhole horizontal well applications. UBD, when properly designed and executed, minimizes or eliminates problems associated with the invasion of particulate matter into the formation as well as a multitude of other problems such as adverse clay reactions, phase trapping, precipitation, and emulsification, which can be caused by the invasion of incompatible mud filtrates in an overbalanced condition. In many UBD operations, additional benefits are seen because of a reduction in drilling time, greater rates of penetration, increased bit life, and potential for dynamic flow testing while drilling.

UBD is not a solution for all formation damage problems. Damage caused by poorly designed and/or executed UBD programs can rival or even greatly exceed that which may occur with a well-designed conventional overbalanced drilling program. Potential downsides and damage mechanisms associated with UBD will be discussed. These include the following:

1. Increased cost and safety concerns.
2. Difficulty in maintaining a continuously underbalanced condition.
3. Spontaneous imbibition and countercurrent imbibition effects.
4. Glazing, mashing, and mechanically induced wellbore damage.
5. Macroporosity gravity-induced invasion.
6. Difficulty of application in zones of extreme pressure and permeability.
7. Political/career risk associated with championing a new and potentially risky technology.

We discuss reservoir parameters required to design an effective underbalanced or overbalanced drilling program, laboratory screening procedures to ascertain the effectiveness of UBD in a specific application and review the types of reservoirs that often present good applications for UBD technology.

Introduction

UBD is a technique in which the hydrostatic pressure in the circulating downhole fluid system, while drilling the well, is maintained at some pressure less than the pressure of the target formation of interest. This condition can be generated naturally with low density fluids (clear water or light hydrocarbon systems) in some situations where high natural pressure exists in the formation. This technique is commonly referred to as flow drilling. In many situations, the underbalanced condition is generated artificially by the concurrent injection of some type of noncondensible gas with the circulating fluid system to reduce effective hydrostatic density. The gas most commonly used is nitrogen because of its availability and ease of transportation, but underbalanced operations have also been executed with air, natural gas, processed flare gas, and reduced oxygen content air (semipermeable membrane unit processed), depending on the specific reservoir situation under consideration. UBD techniques have often been applied for horizontal wells where formation damage concerns have been of particular importance because of longer fluid contact times and a greater prevalence of openhole completions in horizontal vs. vertical well applications. This is because even relatively shallow invasive damage can significantly reduce the productivity of an openhole horizontal well in comparison with a cased and perforated vertical well. Underbalanced technology, however, also has application to vertical wells; therefore, both types of operations will be addressed in this paper.

When the underbalanced condition must be generated artificially, this is most often mechanically accomplished by a process known as drillstring injection. In this process, the noncondensible gas is injected directly into the drillstring at the surface, which reduces the density of the entire circulating fluid system in both the injection path (inside the drillstring) and in the returning fluid flowing back to surface in the annular space outside the string. Specialized surface equipment for pressurized flow, solids separation, cuttings sampling, and well control are required for this operation and has been discussed by other authors1 (Fig. 1).

A drawback of the through pipe injection method is that conventional mud-pulsed logging techniques cannot be used while maintaining an underbalanced condition because of the presence of a compressible gas in the fluid system. In addition, the underbalanced condition may be lost or compromised on a regular basis if jointed drillpipe is used because of the necessity of breaking for periodic pipe connections as the drilling process proceeds. The use of alternate mechanical configurations, such as a parasitic tubing string or concentric drillstring, eliminates this concern and facilitates more continuous underbalanced operation and conventional measurement while drilling (MWD) operations by injection of the noncondensible gas directly into the returning fluid stream at some intermediate location in the annular wellbore.2 Added cost and complexity are the downsides of these applications.

It must be emphasized that because UBD is not a stimulation technique, it may allow us to maximize the potential of existing reservoir strata, but it does not create or enhance existing permeability in marginal quality formations.

Reservoir characterization and the proper placement of the well in viable, producing, reservoir pay obviously play a crucial role in determining the final performance of any well drilled in either an overbalanced or underbalanced mode. The discussion presented in this paper assumes that the well has been placed in a suitable location in the formation of interest and concentrates on procedures for obtaining optimum production rates from known, existing pay.

Advantages of UBD

There are a variety of reasons why UBD may be considered for a given reservoir application and we discuss some of these.

Reduction in Invasive Formation Damage. Many formations are susceptible to a variety of different types of formation damage during conventional overbalanced drilling operations.

1. Physical migration of in situ fines and clays caused by elevated fluid leakoff velocities at highly overbalanced conditions.3
2. The invasion of artificial or naturally generated solids present in the mud system into the formation matrix (particularly an issue in openhole completions where penetration of physically shallow but potentially very severe damage of this type by perforating/fracturing is not normally considered).4
3. A poor knowledge of the formation pore size distribution exists or a significant bimodal size distribution exists that makes the design and formation of a low-permeability sealing filter cake that inhibits deep invasive damage in an overbalanced mode difficult.
4. High-permeability zones presenting the potential for severe invasive fluid loss (large macrofractures, highly interconnected
First, the coefficient $S$ is found by minimizing the relative error between the true and the approximate, and can be given as

$$S = \min \left\{ \sum_{i=1}^{n} \frac{p_{PD}(r_i, z_i, t_i) - p_{PD}(r_i, z_i, t_i)}{p_{PD}(r_i, z_i, t_i)} \right\} \quad \ldots (A-11)$$

With the value of the coefficient $S$ known, the coefficient $R$ is calculated by minimizing the absolute error between the two solutions and is given by

$$R = \frac{\sum_{i=1}^{n} p_{PD}(r_i, z_i, t_i) \times p_{PD}(r_i, z_i, t_i)}{\sum_{i=1}^{n} p_{PD}(r_i, z_i, t_i)^2} \quad \ldots (A-12)$$

The coefficients resulting in a relative error less than 5% (at the wellbore, $r_1 = 1$) are eventually expressed as

$$R = 1.35 - 1.03t_{Dn} + 1.67t_{Dn}^2 \quad \ldots (A-13)$$

and

$$S = 0.83 + 0.44t_{Dn} - 0.33t_{Dn}^2 \quad \ldots (A-14)$$

where

$$t_{Dn} = \log \left( \frac{I_n}{4} \right) \quad (A-15)$$

All details leading to Eqs. A-13 and A-14 are given in Ref. 10. Also, numerous simulations5,10 have shown that for practical purposes one can use $R = 1.35$ and $S = 0.83$; therefore, the pressure buildup analysis is carried out by the application of the principle of superposition as routinely used for conventional well testing purposes.

### References


### SI Metric Conversion Factors

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<tr>
<td>psi</td>
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*Conversion factors are exact.*

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large vugs, extremely high-permeability sands, or intercrystalline carbonates).

5. Susceptibility to aqueous or hydrocarbon phase traps that may result in the retention of water- or hydrocarbon-based invaded fluid filtrates, which may cause a permanent reduction in the productive capacity of the near-wellbore region because of adverse relative permeability effects.2-6

6. Potential adverse reaction between invaded filtrate and the formation (swelling clays, deflocculatable clays, formation dissolution, chemical adsorption, wettability alterations, etc.).

7. Potential adverse reaction between invaded filtrates and in-situ fluids (emulsions, precipitates, and scales).4

Increased Rate of Penetration (ROP). Many UBD operations exhibit significantly greater ROP’s than conventional overbalanced applications. This can reduce drilling time significantly in extended reach horizontal sections, improve bit life, and may reduce drilling costs. Problems with differential sticking, which may be encountered in conventional overbalanced drilling operations, are also obviated. In certain reservoir cases, the prime motivation for UBD has been for these reasons rather than simply formation damage reduction.

UBD Provides a Rapid Indication of Productive Reservoir Zones. Because the hydrostatic pressure of the circulating fluid system in a truly underbalanced operation is less than the formation pressure, a condition of net outflow of formation fluids (oil, water or gas) should occur given sufficient formation pressure and in-situ permeability. Proper flow monitoring of the produced fluids at surface can provide a good indication of productive zones of the reservoir and act as a valuable aid in the geosteering of the well (if a horizontal application). Significant production of liquid hydrocarbons (because gas is usually flared) during the drilling operation may provide some early cash netback to partially defer some of the additional costs associated with the UBD operation.

Logging While Drilling/MWD Through the Use of Electromagnetic Telemetry (EMT) Tools. A major drawback in past UBD operations was the inability to MWD/geosteer when gas-charged fluid systems are used (unless a parasite or concentric drillstring configuration is used, which allows pulsed logging up an entirely liquid-filled drillstring). The development of EMT tools, which directly transmit downhole information back to the surface while drilling, even in an underbalanced mode, have proven highly useful in UBD operations. Depth and temperature limitations and some formation restrictions on these tools still currently limit their applicability in deeper wells but it is expected that, as technology continues to advance in this area, deeper wells will be drilled with this technology. An increased use of coated tubing drilling technology for UBD that utilizes an internal wireline for MWD purposes can also minimize problems associated with MWD operations during UBD.

Ability to Flow/Well Test While Drilling. Recently, several operators have taken advantage of the flow condition occurring during UBD to conduct either single or multirate drawdown tests to evaluate the productive capacity of the formation and formation properties during the drilling operation (in a static mode or while drilling ahead in some situations).

Disadvantages of UBD

The primary reason for drilling in an underbalanced mode must be economically motivated so that an operator feels that the increased cost, and other potential downsides of UBD, are offset by a potential significant increase in well productivity or other technical or operational concerns which can be attributed to UBD. A proper understanding of some of the potential adverse phenomena that may be associated with UBD is essential before implementing any UBD program. These will be discussed now.

Expense. UBD is usually more expensive than a conventional drilling program, particularly if drilling in a sour environment or in the presence of adverse operational or surface conditions (i.e. remote locations, offshore, etc.). Also, as will be discussed in greater detail in the following sections, there is little advantage to drilling a well in an underbalanced mode if the well is not completed in an underbalanced fashion. This often results in additional costs for snubbing equipment required to strip the drillstring from the hole in an underbalanced flow condition. A portion of this expense may be offset by increased ROP conditions resulting in a reduction in drilling and rig time and if the well can be drilled in a truly underbalanced fashion, limited or no completion work will be required, reducing the cost of expensive and extensive completion and stimulation treatments which may often be required in severely damaged horizontal and vertical wells.

Obviously, the major objective in implementing a UBD operation in most cases is to improve well productivity over a conventional overbalanced completion. Therefore, in a properly executed operation, it is expected that the potential downside of increased drilling costs will be more than offset by increased productivity of the well.

Safety Concerns. The technology for drilling and completing wells in an underbalanced fashion continues to improve. Recent developments in surface control equipment, rotating blowout prevention equipment, and the increased usage of coiled tubing in UBD, has increased the reliability of many UBD operations. The fact that wells must be drilled and completed in a flowing mode, however, always adds safety and technical concerns in any drilling operation. The use of air, oxygen content-reduced air, or processed flue gas as the injected gas in a UBD operation, although effective at reducing the cost of the operation, can cause concerns with respect to flammability and corrosion problems. Considerable work has been done recently in high pressure testing to ascertain safe combustible limits of produced mixtures of natural gas, oil, and drilling mud with air, flue gas, and oxygen content-reduced air.2-7

Wellbore Stability Concerns. Wellbore consolidation issues have been a longstanding concern in UBD operations, particularly in poorly consolidated or highly depleted formations. A detailed discussion of this issue is beyond the scope of this paper, but considerable research work remains to be conducted in this area as many horizontal wells have been drilled and completed successfully in an underbalanced condition, even when conventional wisdom and failure calculations have indicated that stability issues should have resulted in formation collapse. Considerable evidence exists, therefore, that stability concerns in many UBD applications may not be as problematic as classically assumed, but a reservoir by reservoir evaluation is required to quantify stability concerns for each UBD application.

SPE Drilling & Completion, December 1998 215
Failure to Maintain a Continuously Underbalanced Condition During Drilling and Completion and Resulting Formation Damage. A major factor in the disappointing results from many UBD operations conducted in the past is that the underbalanced condition is not maintained 100% of the time during drilling and completion operations. Fig. 2a through d illustrate the mechanism of damage associated with this phenomena, and this is elaborated in the literature. The major issue here is that there is no impetus for the formation of any type of classic sealing filter cake on the surface of the rock because the formation pressure is greater than the circulating fluid pressure in a truly underbalanced operation.

Obviously, this is advantageous with respect to formation damage and differential sticking concerns that may be associated with the influx of potentially damaging filtrate or mud solids into the formation, but it also means that the protective ability and presence of this filter cake as a barrier to fluid and solids invasion is negated. If the formation is abruptly (or gradually) exposed to a condition of periodic pulses of overbalance pressure, very rapid and severe invasion of filtrate and associated solids may occur. This problem is often compounded by the fact that very thin, low viscosity, base fluid systems are usually used in most UBD operations to facilitate effective disengagement of the noncondensable gas from the fluid in the surface equipment for solids control purposes. In some UBD situations, the invasive damage is more significant than if a properly designed overbalanced system had been used in the first place because invasive depth and profile can often be minimized in many overbalanced systems with the proper mud and bridging agent design.

Fig. 2—Schematic representation of fluid and solids loss in overbalanced and underbalanced operations.
There are many potential reasons why an underbalanced condition may be lost during drilling.

If a rotary rig is used, the underbalanced condition is potentially compromised each time gas injection must be terminated to make a pipe connection (Fig. 3a). Rapid connections and circulating out to pure gas before each pipe connection tends to minimize the effect of these overbalanced pulses (Fig. 3b), but fluctuations in bottomhole pressure are still common in most operations. The use of real-time downhole pressure measurement equipment to ensure a continuous downhole underbalance pressure condition is essential for a properly executed UBD operation.

Periodic kill jobs to conduct bit trips result in balanced to full hydrostatic pressure being required to control the well unless the string is snubbed out in a flowing mode. A compression wave occurs in front of the pipe when rerunning the string if rapid running of the pipe occurs, which can also aggravate the overbalanced condition. It is recommended for a given underbalanced operation that a new bit be used before drilling if the string cannot be removed in an underbalanced mode and run in slowly after bit replacement. The well should be terminated when the bit is scrubbed if close to the desired total length in the target formation (for a horizontal application), rather than risk impairment of the entire horizontally drilled section to date by a bit trip to obtain a few hundred feet of additional well length.

Periodic hydrostatic kill jobs to conduct conventional mud-pulsed logging programs for MWD and geosteering purposes can have adverse effects caused by fluid invasion. The use of electromagnetic MWD tools can eliminate this problem for wells less than ~8,000 ft in true vertical depth. New EMT tools with repeater transmitters, etc., are extending the effective depth at which this technology can be used, although temperature limitations may still be problematic. Downhole testing for transmission efficiency is often recommended for deep well applications as EMT signals may be degraded/blocking by certain overlying mineral strata, particularly anhydrite-rich zones or other highly resistive formations.

If a concentric or parasitic string configuration is used to obtain a continuous underbalanced condition, full hydrostatic pressure will be present at the jets on the drill bit because a full hydrostatic column of fluid is present in the center of the drillstring. Orifice effects will drop this pressure somewhat when the fluid moves through the jets. Possible flushing and an overbalanced condition may still exist directly at the rock-bit interface that would not be detected by downhole pressure recorders adjacent to the bit because pressure will drop rapidly as the fluid leaves the bit area. Pressure in the majority of the returning fluid column will be controlled by the parasitic/concentric string injection scheme.

Localized depletion effects may occur in situations where formation permeability is low, underbalance pressure is high, or reservoir volume accessed by the well is limited (Fig. 4a). It can be seen, as in any well production application, that a pseudosteady-state flow condition will begin to be forced in zones of the reservoir that have been penetrated during a UBD operation and are in a condition of dynamic flow. In this situation, the flowing equilibrium sandface pressure will ultimately approach that of the circulating underbalanced fluid. It is seen that even a slight increase in effective downhole pressure, which the operator may consider to be well within a condition of true underbalance based on the original reservoir pressure, will result in an overbalanced condition in the near-wellbore region and the potential for fluid and solids invasion. The degree of severity of this problem will depend on the reservoir parameters under consideration and the speed at which the formation tends to repressurize the depleted zone during the overbalanced period.

The problem is generally more severe in lower permeability zones where significant near-wellbore drawdown gradients may occur (Fig. 4b). Although high-permeability formations will repressurize more quickly and be less sensitive to this type of damage, it is also likely that these zones will be operated in a less under-
balanced condition because of surface flow restriction considerations. This means that there will be less margin for error in an overbalanced pulsed situation because we would be operating much closer to the original reservoir pressure in this situation than in a lower permeability scenario. The optimum operating procedure to minimize the impact of this phenomena is to have a situation of gradually increasing underbalance pressure as the zone of interest is drilled. This ensures that every portion of the formation is maintained in a state of gradual, but continuously increasing, drawdown.

The majority of UBD applications to date have been in horizontal wells. In this situation, the true vertical depth of the target zone is relatively constant, making hydrostatic column height and density, which will control the underbalance pressure level, relatively constant. For a UBD operation in a vertical well, if the target pay zone is relatively thin, a similar situation exists. More significant problems may occur if a UBD operation is implemented in a vertical or deviated well where thick, multiple pay zones are to be penetrated. In this situation, the hydrostatic head of fluid in the vertical relief of the target zone may exert a significant influence on pressure at the base of the well. Therefore, although an underbalance condition may be present upon penetration of the zone, if gas/liquid rates are not adjusted as drilling proceeds, this underbalance condition will be continually degraded as more and more vertical column is added to that already present in the wellbore. The optimum situation in this mode is to maintain a continuous pressure at the bit, which will result in a natural and desirable gradual increase in underbalance pressure in uphole sections of the well.

A poor knowledge of original reservoir pressure may result in operating in an overbalanced condition. Good metered flow of excess oil, water, or gas from the formation is a good indication that a true UBD condition has been achieved (at least in some portion of the exposed reservoir), but may not always be practically measured in formations that exhibit very low-permeability and correspondingly low-production rates.

The intersection of multiple reservoir zones, which may be at significantly different pressures because of the presence of permeability barriers, may result in crossflow between individual zones and a condition where underbalanced conditions may be obtained in some higher pressure zones and overbalanced conditions in lower pressure zones penetrated by the well. Design criteria for effective UBD in these situations dictate that the underbalanced condition must be designed to accommodate the lowest pressure-productive interval expected to be encountered. This is often impractical, particularly if significantly higher pressure, high-permeability zones are present.

A variation on the previous scenario, and perhaps more common, is a horizontal UBD operation in a single zone that exhibits a significant areal variation in pressure over the length of the well (i.e., localized depleted low-permeability formations, mature waterfloods with zones of high/low pressure). This creates problems similar to the previous case in that, once again, the UBD operation needs to be designed to accommodate the lowest (and often unknown) pressure zone that will be encountered.

Slug flow and liquid holdup occur in the vertical section of the wellbore in most UBD operations where gas and liquid are being concurrently injected. This results in problems with sizing of surface equipment to handle periodic high rate surges that occur at surface conditions and downhole pressure swings and surges that may be comparable in magnitude with those induced in making pipe connections in rotary drilling operations, and may result in invasion in lower pressure/depleted zones of the reservoir. At significant depths and high gas flow rates, fractional pressure drops can be significant in the string and returning annular fluid space. In certain flow regimes, fractional pressure effects may actually cause an increase in effective bottomhole pressure with an increase in gas injection rate, counterintuitive to what would normally be expected. A more detailed discussion of these phenomena is provided in the literature.12

Because the underbalanced condition, in many situations, is a condition that is naturally foreign to the drilling process, it must be maintained by delicate control and the use of special surface injection and control equipment. Unfortunately, this means that the operation is at the mercy of smooth and trouble-free operation of all the equipment on the lease and uninterrupted supply sources of the noncondensable injected gas to ensure a continuously underbalanced condition. In many operations, or supply problems occur that may result in the physical loss of the underbalanced condition for a period and may negate much of the effort expended to drill underbalanced in the portion of the well drilled before that time.

Overbalanced/Conventional Completion/Kill Jobs. Much of the benefit of UBD may be negated if conventional completion practices are used after the drilling operation has been completed. This is particularly true if the formation is sensitive to fluid invasion (either chemically or from a relative permeability/trapping perspective); therefore, if the commitment has been made to drill underbalanced to obtain maximum benefit, underbalanced completion procedures should be used. This obviously may increase costs in many situations and preclude obtaining desirable log suites in some wells, but the final objective is to obtain a significant increase in well productivity. These are all factors that must be carefully considered and planned before implementation of the UBD program.

Spontaneous Imbibition and Countercurrent Imbibition Effects. Because of adverse capillary pressure effects, it is possible to imbibe water-based (and in some cases hydrocarbon-based) fluids into the formation in the near-wellbore region where they may cause a reduction in permeability because of rock/fluid or fluid/fluid incompatibility effects, or a reduction in flow capacity because of aqueous or hydrocarbon phase trapping and relative permeability effects. The absence of a sealing and very low-permeability filter cake, which can act as a barrier to long-term spontaneous imbibition effects (as long as high initial spurt loss is not present) created during a conventional well-designed overbalanced drilling operation, potentially, can result in more severe problems with imbibition being present in a UBD operation than in a normal overbalanced situation. A detailed discussion concerning aqueous phase trapping and countercurrent imbibition effects is contained in the literature.5,6 In an UBD operation, imbibition effects may cause phase trapping and damage problems in a number of different reservoir scenarios.

Water-wet gas reservoirs that exist in a dehydrated state of subirreducible saturation are common in very tight gas reservoirs in zones that have undergone significant regional migration of gas over geologic periods of time. Fig. 5 illustrates the phenomena of spontaneous countercurrent imbibition for a reservoir of this type. Because of the very low initial water saturation, there is a very strong tendency to countercurrently imbibe the water-based mud filtrate into the formation to reach an equilibrium capillary pressure value. The greater the difference between the initial and true irreducible water saturation exhibited by the formation, the more severe the problem. Because of the asymptotic nature of most capillary pressure curves near the irreducible water saturation, the practical magnitude of applicable underbalance pressures are insufficient to counteract most countercurrent spontaneous imbibition effects. The severity of damage associated with this imbibition effect will be highly dependent on the configuration of the gas phase relative permeability curve in the region of low-liquid saturation.

Equivalent imbibition effects can occur with hydrocarbon-based fluids in oil-wetted formations that exhibit subirreducible oil saturations. This can occur in oil-wetted retrograde condensate formations producing under the dewpoint pressure, in gas-bearing formations containing naturally oil-wetted minerals (i.e., pyrobitumen, elemental sulfur, asphaltic precipitates, or residual heavy bitumen saturations), or in gas reservoirs exhibiting very low subirreducible oil saturations caused by displacement of an original oil column from the zone by gas over geologic time.

Water-wet formations, in general, will not spontaneously imbibe oil-based fluids and, conversely, oil-wetted formations will not
imbibe water-based fluids (although if high-fluid loss conditions exist in an overbalanced scenario, these fluids can still be easily displaced by pressure in a damaging fashion into the near-wellbore matrix). Thus, a proper understanding of formation wettability coupled with the base fluid selection for a UBD program can minimize some of the problems associated with countercurrent imbibition effects.

Glazing, Mashing, and Cuttings Damage. In any drilling operation, drill cuttings are generated by the erosive action of the drillbit on the formation. Additional solids may be added to the circulating fluid system on occasion to improve mud rheology and properties. The size and quantity of cuttings in the circulating fluid stream depends on the formation type, surface, solids control equipment, bit type, ROP, and fluid system under consideration. Fluid systems used in UBD operations and gas/air drill operations may suffer from problems caused by the following.

Glazing is a polishing of the surface of the wellbore caused by direct action of the bit at the formation face (particularly severe when drilling hard formations at low ROP's or with dull or damaged bits). Mashing is a polishing of the formation face by poorly centralized or sliding drillstring. The glaze generally consists of formation fines that are generated and milled by the drillbit action, which forms a thin, pottery glaze like paste and coats the surface of the formation. Straight gas drill operations are particularly sensitive to this problem because of the poor solids transport properties of most pure gas systems, very fine dust-like cuttings that are generated, and the poor heat transfer capacity of gas, which results in very high rock-bit temperatures and aggravates the glaze formation process. Mashing, caused by poorly centralized rotating string and sliding, can occur in any drilling situation where large amounts of downhole solids are present.

Glazing and mashing, in general, tend to be relatively shallow processes with the physical depth of the damage extending only a few millimeters into the formation; therefore, cased and perforated completions rarely encounter significant impairment in productivity caused by this problem because the damage is easily penetrated with a typical perforation charge. Very heterogeneous formations containing large vugs or natural fractures also tend to be less sensitive to this type of damage because of the inability of the glaze to occlude large porosity features of this type. Relatively homogeneous sandstone or carbonate formations completed in an openhole mode, therefore, tend to be the most susceptible to this type of damage. In carbonate formations, the glaze tends to be dominated by acid-soluble limestone or dolomite constituents and can often be removed by a tubing-conveyed light acid wash. This is in comparison with the more difficult to remove silicate-based glaze generated in sandstone formations.

Macroporosity Gravity-Induced Invasion. In formations that exhibit macroporosity (very large open fractures, large interconnected vugs), physical gravity-induced invasion of circulating drilling fluid and solids can occur into these features on the lower side of a horizontal wellbore (Fig. 6). If the fractures or vugs are small and the underbalance pressure sufficient, the natural orifice jetting action of the fluid from these features into the wellbore will be sufficient to counteract this phenomena, but if low underbalance pressures or very large porosity features are present resulting in a low superficial fluid velocity at the wellbore-porosity feature intersection, gravity-dominated invasion may occur in some situations. This can result in lost circulation, even though continuously underbalanced conditions are being maintained.

Difficulty of UBD Execution and Control in Zones of Extreme Permeability. It is unfortunate that one of the best applications of UBD technology, that of extremely high-permeability formations (i.e., macrofractured chalks, grossly vugular carbonates, highly unconsolidated high-permeability sands) also presents one of the major challenges in UBD. Effective control of these formations when they exist at naturally high initial pressure, even at relatively low underbalance pressure conditions, becomes problematic, and the risks associated with handling huge volumes of produced fluids and high pressures on surface become too costly and risky to consider a UBD operation, particularly in extreme or offshore operating conditions. Improvements in surface handling and control equipment may allow UBD technology to be applicable to a wider spectrum of formation applications of this type as the technology for UBD continues to advance.

Career and Political Risk of Failure. UBD, like any advanced technology, often needs a company champion to step forward and
present a case for a good application of a UBD operation. In many companies, having a successful first application of any new technology is important for that technology to be considered for future application. Therefore, proper selection of a good candidate reservoir for UBD is doubly important for a first operation because a poorly executed operation resulting in a failure will more often than not result in the technology being discounted as too risky for future applications where it may, in fact, provide significant economic advantage to a conventional underbalanced operation.

Case Studies

The following case study provides a good illustration of the importance of maintaining a continuously underbalanced pressure condition during drilling and completion. The subject horizontal well was drilled in a low-permeability (2 md) carbonate formation exhibiting a subirreducible 15% water saturation. Because of known problems with aqueous phase trapping and imbibition, underbalanced wells completed in the past had performed poorly. The decision was made to attempt to drill underbalanced with a nitrogen/hydrocarbon mist system. The well was drilled approximately 100 psi underbalanced and exhibited favorable peak flow rates of 5,000,000 to 7,000,000 scf/D during the UBD operation; subsequently, the well was killed with a water-based kill fluid to facilitate conventional completion. On a post-cleanup basis, an over 50-fold reduction in productivity index was observed because of the loss of the underbalanced condition and subsequent establishment of an aqueous phase trap in the near-wellbore region.

Conversely, a recently drilled horizontal oil well in the Rigel C Pool was conducted in which extra care was taken to maintain a continuous UBD condition which yielded very favorable results with peak flow rates of over 7,000 B/D during the UBD operation and zero tested skin on a post UBD basis.

Laboratory Screening Techniques

A variety of laboratory techniques are available to quantify the effect of UBD on a given formation. The specifics of the equipment and procedures used for this type of testing have been described in other work and a schematic illustration of a typical underbalanced coreflooding evaluation apparatus appears in Fig. 7. A basic suite of tests conducted to contrast overbalanced vs. UBD operations follow.

Underbalanced Laboratory Evaluation

1. Obtain representative preserved or restored state samples at correct initial oil and water saturation conditions.
2. Measure initial, undamaged reference permeability to oil or gas (depending on the reservoir type under consideration) at varying conditions of drawdown pressure encompassing the range of expected field drawdown pressures (to observe presence of capillary or turbulence effects).
3. Conduct a UBD fluid test by circulating the proposed drilling fluid in an underbalanced mode across the core face with the maximum expected underbalance pressure gradient across the core while continuously tracking permeability for a 24-hour period or until a stabilized dynamic permeability is obtained.
4. Conduct a liquid test with gas or oil to determine the threshold pressure required to mobilize any damage induced by the overbalanced pulse and ascertain if damage is reduced by increasing drawdown pressure and final amount of damage remaining at the maximum expected drawdown pressure (if damage is severe, potential stimulation treatments could be evaluated at this time).
5. Conduct a variable drawdown pressure return-permeability test with gas or oil to determine the threshold pressure required to mobilize any damage induced by the overbalanced exposure and ascertain if damage is reduced by increasing drawdown pressure and final amount of damage remaining at the maximum expected drawdown pressure (if damage is severe, potential stimulation treatments could be evaluated at this time).

This procedure provides a good indication as to whether countercurrent imbibition effects are going to be problematic and how much underbalance pressure must be maintained to minimize their effect. An indication of the severity of formation damage and depth of invasion to be expected if the underbalanced condition is compromised can also be provided by this type of test as well as the ability of formation pressure (or stimulation treatments) to remove the damage.

Overbalanced Laboratory Evaluation

1. Core procurement and initial permeability measurements are identical to those described previously for the underbalanced laboratory tests.
2. Conduct an overbalanced drilling fluid test by circulating actual field quality mud (containing drill and mud solids and bridging agents) in a turbulent fashion across the core face at the maximum expected overbalance pressure. Observe fluid loss rates, filter-cake buildup, and sealing potential and depth of filtrate and solids invasion. A spectrum of muds from conventional systems, which may commonly be used (i.e., gel chemical) to more sophisticated polymer-type (MMH, etc.) blends with specialty-sized bridging and fluid loss agents, may be evaluated to obtain the optimal system for overbalanced operations.
3. Conduct a variable drawdown pressure return-permeability test with gas or oil to determine the threshold pressure required to mobilize any damage induced by the overbalanced exposure and ascertain if damage is reduced by increasing drawdown pressure and final amount of damage remaining at the maximum expected drawdown pressure (if damage is severe, potential stimulation treatments could be evaluated at this time).

This test sequence illustrates how damaging a conventional overbalanced drilling program may be (in comparison with either a well-executed or poorly executed underbalanced program from the proceeding test program matrix) and provides an indication if comparable or superior potential performance may be obtainable at less cost and risk from a specially tailored conventional-type drilling system in comparison with an underbalanced operation. Additional details on this type of test procedure are provided in the literature.
Types of Reservoirs Suitable for Underbalanced Drilling

On the basis of the information presented, certain types of reservoirs are more applicable for UBD operations than others. Prime reservoir types where UBD has been successful in the past include the following:

1. High permeability (>1,000 md) consolidated intercrystalline sands and carbonates. At high formation pressures, well control issues may limit the utility of UBD because of surface processing and handling issues.
2. High permeability poorly/unconsolidated sands (some risk of wellbore collapse present in some situations, however, a number of underbalanced operations have been conducted successfully in unconsolidated sands). At high formation pressures, well control issues may limit the utility of UBD because of surface processing and handling restrictions and sand production issues.
3. Macrofractured formations (fracture apertures generally greater than 100 μm) if fracture aperture starts to exceed 1,000 to 2,000 μm, some possibility of gravity-induced invasion on fractures on the bottom of the wellbore exists at low underbalance pressures. At high formation pressures, well control issues may limit the utility of UBD because of surface processing/handling issues.
4. Underpressured/depleted formations where conventional drilling would exert more than 1,000 psi hydrostatic overbalance pressure.
5. Formations containing significant concentrations of water-based mud filtrate-sensitive materials (expandable clays (>1%), defloculatable clays (>5%), anhydrite, halite, etc).
6. Formations exhibiting severe potential incompatibility issues with base filtrates (emulsions, sludges, precipitates).
7. Dehydrated formations exhibiting subirreducible water saturations or hydrocarbon saturations may be candidates for UBD with the appropriate based filtrate to avoid countercurrent imbibition and phase-trapping problems (water for oil-wet systems and oil for water-wet systems).

Warning Flags for Underbalanced Drilling

1. High pressure zones exhibiting high flow and potential control problems.
2. Large pressure pulses occurring because of pipe connections, mud-pulsed MWD logging, bit trips, bit-jetting effects, localized depletion effects at high drawdown rates, and uncertain knowledge of original reservoir pressure.
3. Multiple reservoir zones at differing pressures with variable pressure in a given zone.
4. Excessive slug flow and liquid holdup in the vertical section of the well.
5. Locations where supply or mechanical problems are likely to occur.
6. Use of water-based systems in dehydrated (irreducible water saturation) tight gas reservoirs.
7. Air/gas drilling in lower permeability homogeneous sandstones (glazing).

UBD has specific applications. Formations exhibiting uniform matrix qualities, average to low permeabilities, normal pressures, and an absence of potential rock or fluid incompatibilities can often be drilled and completed successfully at a lower cost with conventional drilling technology if a proper understanding of reservoir parameters is obtained. Only through careful reservoir characterization can it be determined which reservoirs are the prime candidates for viable application of UBD technology to obtain a maximum return on investment.

Conclusions

We have discussed the potential advantages and disadvantages of UBD operations and presented a list of potential damage mechanisms and high risk areas associated with UBD. Screening tests and criteria to consider when evaluating whether a particular reservoir is a candidate for UBD have been presented. Experience has indicated that in the right circumstances significant technical and economic benefits can be obtained when care is taken in the design of a UBD program. Conversely, application of a poorly conceived and executed UBD program can often result in additional costs, greater damage, and reduced production compared with a well-designed conventional overbalanced program.

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References


SI Metric Conversion Factors

\[
\begin{align*}
\text{ft} \times 3.048^* & \quad \text{E} - 01 = \text{m} \\
\text{ft}^3 \times 2.831 \, 685 & \quad \text{E} - 02 = \text{m}^3 \\
\text{psi} \times 6.894 \, 757 & \quad \text{E} + 00 = \text{kPa}
\end{align*}
\]

*Conversion factor is exact.

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