UNDERBALANCED DRILLING TECHNOLOGY -
CANDIDATE SELECTION FOR OPTIMAL APPLICATION

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Abstract

Underbalanced drilling (UBD) is used increasingly worldwide as an alternative technique to conventional overbalanced drilling to reduce invasive near wellbore formation damage problems in oil and gas producing formations. Properly designed and executed underbalanced drilling operations can eliminate or significantly reduce formation damage concerns with respect to such phenomena as mud or drill solids invasion, lost circulation, fluid entrainment and trapping effects, and potential adverse reaction of invaded drilling or completion fluids with the reservoir matrix or in-situ reservoir fluids.

Underbalanced drilling and completion operations are not necessarily a panacea for all formation damage problems and, if an underbalanced drilling operation is poorly designed and executed, there is the potential for greater damage than if a properly implemented overbalanced operation had been used.

What Is Underbalanced Drilling?

By rigid definition, an "underbalanced" condition is generated any time the effective circulating downhole pressure of a drilling, completion, stimulation or workover fluid (the pressure exerted by the hydrostatic weight of the fluid column, plus whatever pump pressure is applied to the fluid system to circulate or inject it, and the associated frictional pressure drop) is greater than the effective pore pressure in the formation adjacent to the sand face. Most formations, unless abnormally pressured, are naturally placed in an overbalanced state when water based fluids of normal density are used in typical oilfield operations. In some abnormally high pressured formations (and in some normally pressured formations), a naturally underbalanced condition can be generated using conventional oil- or water-based drilling fluids. This condition, if it occurs during a drilling operation, is normally termed "flow drilling" and has been used successfully for many years in formations such as the Austin Chalk in Texas.
Most of the current discussion related to underbalanced drilling, and that which this article focuses on, is a condition where the formation pressure is sufficiently low that an effective underbalance pressure cannot be achieved downhole without the entrainment of some type of non-condensable gas with the circulating drilling fluid to lower the effective fluid density to the point where an underbalanced condition is obtained. This is often referred to as the "artificial" generation of the underbalance condition.

Advantages of Underbalanced Drilling

Some of the advantages of underbalanced drilling include:

- Potential reduction in invasive formation damage
- Minimize the potential for lost circulation
- Minimize the potential for differential sticking
- Eliminate need for costly mud systems and costly disposal of exotic muds
- Improved ROP on drilling, reducing drilling costs and increased bit life
- Mitigation of extensive and expensive completion and stimulation operations
- Rapid indication of productive zones of the reservoir during drilling
- Potential economic benefit from flush production during drilling
- Potential to flow test while drilling

Disadvantages of Underbalanced Drilling

Many studies have investigated some of the potential disadvantages of the UBD process, particularly if poorly designed and executed. These would include such concerns:

- Wellbore stability and consolidation concerns
- Safety and well control concerns in high pressure or sour environments
- Increased costs for drilling (and complex completions if required due to the essential nature of completing the wells in a live condition)
- Inability to use conventional MWD technology for through string injection techniques
- Failure to maintain a continuously underbalanced condition resulting in significant invasive damage because of periodic overbalanced pressure pulses due to:
  - Pipe connections
  - Bit trips
  - Conventional MWD signal transmissions
  - Localized depletion effects
  - Frictional flow effects
  - Hydrostatic column effects
  - Multiple different pressured zones
  - Variable pressure in a common zone
  - Poor knowledge of original reservoir pressure
  - Operational or supply problems

Spontaneous Countercurrent imbibition effects
Gravity drainage effects in high permeability zones, even under constant underbalanced flow conditions
Condensate dropout/gas liberation effects
Glazing or mashing (near wellbore mechanical damage)
Increased propensity for corrosion problems if air or oxygen content reduced air is used as the non-condensable gas medium used to generate the underbalanced condition

The underbalanced condition must be maintained continuously; however, even more significant damage may have occurred than in the conventional overbalanced situation due to the low viscosity fluid, high solids content and lack of a protective filter cake present during the UBD operation if the underbalance condition is compromised. This is schematically illustrated in Figure 1.

What Are The Issues to Be Addressed

Underbalanced drilling is not a solution to poor reservoir quality. The process does not inherently manufacture permeability. It can, however, yield significant increases in production if the problem with conventional overbalanced completions has been a high degree of formation damage which cannot be overcome by conventional fluid or operational design practices (ie - severe lost circulation, extreme permeability zones, significant pressure depletion, major rock-fluid sensitivity issues with reactive clays, emulsions, etc.), or if technical problems (differential sticking) have occurred. Many operators attempt to apply UBD technology in extremely poor quality formations, expecting high production rates when, even if the well is
drilled and completed in a completely undamaged fashion, productivity is uneconomic due to permeability limitations. The application of UBD technology in horizontal wells to attempt to intersect macro or microfractures in a low permeability matrix, or to obviate gas or water coning problems in vertical wells, would be potential exceptions to this rationale.

Often, underbalanced drilling technology is not given a fair assessment as it is often considered an expensive alternative to conventional overbalanced drilling which is expected to solve a vast array of impaired productivity problems and is, therefore, applied in situations of marginal reservoir quality where we know that a conventional overbalanced approach has not been successful. This, perhaps, is one of the reasons why we see a relatively high economic failure rate among UBD projects as the field of applications have, in general, been biased towards more marginal quality reservoirs in many situations.

The majority of these through string injection UBD projects have been conducted using water-based fluids (often produced water) and nitrogen. The average gas injection rates have typically been in the range of 30-40 m³/min (1.5 - 2.0 MMscf/day), although this is highly dependent on the reservoir pressure and the amount of reservoir gas which can be produced to assist in the UBD operation once the producing zone has been penetrated. In UBD operations executed in gas reservoirs, once penetration of the zone occurs, the UBD operation may be partially self-supporting with the produced gas, and very little supplemental gas may be required with sufficient fluid injection required only for adequate downhole motor and drilling operations.

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The main criteria in deciding whether or not to implement UBD technology in a given reservoir situation are:

1. Considering past experience, can this well be drilled and completed using overbalanced technology? (Note: Not necessarily the same overbalanced technology that has been used in the past which gave marginal or disappointing results).
2. Based on an engineering evaluation of reservoir parameters, do we feel that UBD will provide a significant technical or economic advantage to the project?
3. What is the risk of failure/problems associated with the UBD operation?
4. Does the expected increase in value justify the increased risk relative to the conventional overbalanced drilling/completion practices?

Overview of Current UBD Processes

Figure 2 provides a schematic illustration of a typical UBD process using a closed surface control system. The vast majority of UBD operations executed to date have utilized jointed drill pipe and the direct injection of the base drilling fluid and some type of noncondensible gas directly down the centre of the drill string. This is not necessarily because this is the best technology to use, but because it is the least expensive and easiest to execute with the number of rotary rigs and conventional drilling equipment available.

Many early UBD operations did not have the ability to conduct real time downhole pressure measurements, resulting in many supposedly underbalanced wells being drilled in a completely or periodically overbalanced state. Later improvements used memory pressure gauges which allowed acquisition of downhole pressure profiles, but only after the fact and damage had been done, when it was ascertained that a continuously underbalanced condition had not been maintained. The more recent development of EM downhole tools, capable of transmitting downhole pressure and survey data directly back to surface via an electromagnetic pulse or CT applications with an internal wireline for direct downhole data transmission, have greatly enhanced the technology for UBD by allowing real time acquisition of pressure and location data while drilling.
The Use of Coiled Tubing

In many aspects coiled tubing is a system which is custom designed for an effective underbalanced drilling process. The advantages of coiled tubing are obvious in that the single unjointed pipe facilitates the ready operation of the UBD process in a continuously underbalanced mode. The use of an internal wireline facilitates accurate real time MWD measurements which may be significantly less problematic than EMT tools and surface pressure operating constraints with coiled tubing are much greater (10,000 psi) in comparison to the limited pressure range of 1500 psi currently offered by the majority of rotating control heads used in jointed pipe UBD operations. Coiled tubing technology has now proven to be a viable and practical method for the effective drilling of horizontal and vertical wells, especially in re-entry work out of smaller casing sizes, deepennings and sidetracks where one wants to just barely enter the zone to get flow back to surface plus the re-entering of existing horizontal wells to drill more extensions and legs underbalanced. As the technology continues to improve there is definitely going to be a niche market for CT services in the area of underbalanced drilling.

The disadvantages of coiled tubing are the time and commitment involved to use a new technology, availability of equipment, concerns over accurate depth control and safety concerns in high pressure wells with large volumes of pressurized gases at surface in the exposed non-injected CT string. Also of concern are depth control and reach limitation for horizontal drilling applications. The major current challenge for a CT operation is obtaining the experienced personnel and mobilizing the equipment on site to make the technology a cost effective serious contender with the more readily available and heavily favoured jointed pipe systems.

What is the Best Operational System to Use?

This question must be answered from a technical, safety and economic point of view. Technically, the system which will yield the best bottomhole pressure control with a continuously underbalanced condition is optimum with the required necessity of continuous real time bottomhole location and pressure measurements. This heavily favours coiled tubing (particularly for small diameter holes and re-entries), but cost, availability and required horizontal reach may eliminate CT as a serious contender. Alternate parasite string or annular injection techniques may also be considered. These techniques are often costly and, from an abandonment perspective, may be more problematic for the parasite string approach. The presence of the weight of a full hydrostatic column of fluid in the drill string may result in a zone of localized overbalance pressure and flushing at the bit and around the BHA, if pressure drop in the motor assembly is low, and frictional losses around the BHA are high enough to create a restricted flow zone. Jointed pipe operations will likely continue to be used in the majority of systems for the next few years until CT costs and availability, plus improvements in CT technology, allow it to assume a more dominant position in the UBD marketplace.

What Are the Optimum Operating Conditions?

The question is often asked as to what type of underbalance pressure gradient is required for an effective UBD operation. Typically, circulating pressures sufficient to yield a 10-30% drawdown are often considered normal, but this is highly reservoir specific. In high pressure and high permeability formations this may yield uncontrollable flow rates at surface and possibly contribute to premature water or gas coning or hydrocarbon dropout in rich gas systems. Current surface control equipment exists to handle up to 2.8x10^6 m^3/day (100 MMscf/day) of gas flow and up to 4000 m^3/day (25,000 bbl/day) of produced fluids, but detailed evaluation of the flow control and coning characteristics of the target formation must be carefully evaluated prior to implementing the UBD operation and designing the effective required UBD drawdown gradient.

Any UBD operation results in localized depletion effects occurring in the near wellbore region as illustrated in Figure 3. Periodic slight increases in circulating pressure, even if the operator feels that an underbalanced condition is still being effectively maintained at the bit, can result in potential overbalanced fluid invasion into a previously drilled section of the horizontal wellbore. These oscillations in BHP are natural occurrences during pipe connections, slug flow, system upsets and as the base system mud weight increases due to a higher solids load as the mud and fluid system is used for a greater period of time (due to the generally mediocre solids separation capability of most surface control systems used in typical UBD operations). This phenomenon may be partially counteracted by gradually attempting to increase the effective underbalance pressure as the well is drilled to maintain every section of the formation, regardless of the time at which it was drilled, in a continuous state of gradually increasing drawdown which will ensure that a continuous underbalance condition is uniformly maintained throughout the well. Increases in effective drawdown gradient of 5-10% over the length of the horizontal section are recommended to counteract this effect. Such reductions
in pressure may not always be possible due to frictional backpressure effects and formation inflow which may occur during the drilling operation. Natural frictional pressure losses will also mimic this effect if efforts are maintained to keep a consistent pressure at the bit as the drilling operation proceeds.

**Screening for UBD Process Selection**

Many factors must be considered by the integrated team to ascertain if a particular reservoir is, in fact, a prime candidate for an underbalanced drilling operation. The following section provides some examples of some common reservoir types which are and are not generally suitable for consideration as UBD candidates.

**Potential Prime Reservoir Applications for UBD**

**Reservoirs with Significant Loss Circulation or Fluid Invasion Potential (fractures, vugs, extreme permeability consolidated/unconsolidated intercrystalline formations and zones of extreme pressure depletion)**

This would include zones of extreme intercrystalline permeability (1000 mD and greater), large macroscopic open fractures, heterogenous carbonates with massive interconnected high permeability vugular porosity, zones of extreme pressure depletion (resulting in extreme overbalance pressures of 7 MPa or greater) or the worst case scenario of a combination of one of these types of high permeability features in a significantly pressure depleted situation.

These reservoir candidates are prime applications for underbalanced drilling due to the difficulty, particularly in the fractured and heterogenous carbonate situations, of designing effective overbalanced fluid systems which will generate uniform and stable filter cakes which will prevent significant invasion of the near wellbore region by potentially damaging mud filtrate and solids, yet still be readily removable to allow unrestricted flow from the formation. When filter cakes do form in situations such as they often tend to result in problems with differential sticking which can lead to expensive and sometimes terminal problems associated with stuck pipe.

Some fluid losses may occur when drilling horizontal wells in systems exhibiting extreme macroscopic permeability features due to gravity induced drainage.

**Formations Exhibiting Extreme Rock-Fluid Sensitivity**

Considerable formation damage can be caused by the adverse reaction of incompatible water based filtrates with in-situ clays or other reactive materials. Many formations contain hydratable clays such as smectite or mixed layer reactive clays. These clays will expand on contact with non-inhibited water based systems and can significantly affect productivity and, in some cases, near wellbore consolidation. Some formations may also contain defloculatable clays and fines or velocity migratable materials (ie - kaolinite clay, detrital rocks fragments, pyrobitumen, anhydrite, etc). Many of these types of problems can be addressed through the appropriate use of overbalanced technology with hydrocarbon based or inhibitive water based fluids.

**Formations Exhibiting Significant Fluid-Fluid Sensitivity**

The invasion of incompatible drilling fluid filtrates into the formation can result in potential incompatibility between these invading fluids and the in situ formation brine or oil. Reactions could include the formation of extremely viscous oil in water emulsions which may become entrapped in the near wellbore region and cause reductions in permeability, deasphalting of in situ reservoir crude caused by contact with incompatible invading foreign hydrocarbon based fluids or the formation of scales and precipitations caused by reaction with water based filtrates and in-situ formation brines.

Appropriate geochemical testing and compatibility testing can generally eliminate this problem for most conventional overbalanced operations. Conversely, in some situations where the potential for damage is extreme, UBD may be contemplated as a mechanism to avoid the introduction of the potentially reactive material into the formation in the first place.

**Formations Exhibiting Subirreducible Oil or Water Saturations**

The mechanism of aqueous and hydrocarbon phase trapping has been discussed in detail in the literature.11 Permanent entrapment of water or hydrocarbons in the near wellbore region can result in significant reductions in the productivity of the formation due to adverse relative permeability effects. Underbalanced drilling, if the wrong base fluid is used, may aggravate this problem due to spontaneous countercurrent imbibition effects4, but if appropriate designed UBD technology can be an efficient means of mitigating potential problems with adverse fluid retention and trapping effects. Use of a non-wetting fluid as
the base fluid for and UBD operation will generally negate the potential for spontaneous imbibition and reduce the potential for phase trapping as long as a continuously underbalanced condition is maintained and we avoid the direct displacement and entrapment of the base drilling fluid into the formation.

**Formations of Highly Variable Quality**

Highly laminated formations or more massive sandstone or carbonate formations which exhibit a wide variation in reservoir permeability and porosity (i.e., a large variation in pore throat size distribution) represent major challenges with respect to designing effective overbalanced fluid systems which will effectively bridge and protect the wide range of pore features that exist in these situations. In general, overbalanced systems are designed in these scenarios to attempt to protect the better quality portions of the matrix, as this is expected to be the zone from which the majority of production occurs. This can result in significant damage to portions of potentially productive formation in some cases. The use of UBD technology in some of these situations may result in more uniform production from the target interval.

**Formations Exhibiting Low ROP**

The preceding motivations for UBD primarily centered about formation damage, drilling execution and production concerns. For some hard rock formations significantly greater ROP’s can be obtained with UBD due to greater weight on bit. This may significantly reduce drilling times and associated costs. In a limited number of cases the primary motivation for UBD in some operations has been for purposes of ROP, rather than some of the previously mentioned factors.

**Major Reservoir Criteria Which Contraindicate Underbalanced Drilling**

**Combinations of Extreme Pressure and Permeability**

Although deep, high pressure, high permeability zones represent perhaps one of the best potential applications for UBD from a formation damage perspective, safety and control issues with respect to well control at the surface may become problematic when downhole pressures in excess of 30 MPa are contemplated (particularly in gas reservoir applications) when using conventional rotary drilling equipment and rotating diverter heads. The use of coiled tubing drilling in such a situation is preferable, as surface pressure ratings are much higher, but conversely if high surface injection pressures are required then a large volume of pressured fluid in present at surface in the uninjected CT string which may also present a potential safety hazard.

**Situations Where a Continuous Underbalance Condition is likely to be Compromised**

This is one of the single greatest flags to an underbalanced drilling operation. Much of the benefit of UBD is lost and the operator may actually be in a greater damage scenario if underbalanced conditions are not maintained continuously during both the drilling and completion operations. There is little advantage to drilling in an underbalanced mode (unless increased ROP is the only motivation for UBD), and then using normal overbalanced practices to complete the well. It should be emphasized that real-time downhole pressure measurements are essential to ensure the success of any UBD operation, finding out after the fact that we were not underbalanced is little consolation for a failed job. The use of EMT technology for conventional jointed pipe drilling has greatly improved the ability to monitor downhole pressures in these operations (without periodically pulsing the formation with overbalance pressure for conventional MWD operations or using costly parasite or concentric string approaches). The reliability of EMT technology still limits its use in deeper formations (greater than 2500 m), but current improvements, such as mid-string repeater stations, promise to extend the technology to potentially deeper applications.

Coiled tubing drilling represents what many feel is the future in UBD due to our ability to maintain a relatively continuously underbalanced condition and MWD using a less problematic internal wireline approach. Current CT technology is limited with respect to depth and horizontal outreach capability for extended reach well applications. Pressure pulses during connections with a conventional jointed pipe can be minimized by using double pipe stands, rapid connections and appropriate circulation practices prior to breaking for connections to minimize the degree of degradation of underbalance pressure that occurs during or after the connection is made. Top drive rigs offer the advantage of drilling with triple pipe stands which further reduces the number of connections required.

Other factors would include any type of reservoir where any type of hydrostatic kill would be required for specialized completions, bit trips, etc.

**Reservoir Pressure Constraints**

Reservoirs which may exhibit zones of multiple different
pressures or a significant areal variation of pressure in a
given target zone may be difficult candidates for UBD.

*Normally Pressured Intercrystalline Formations of Less
Than 500 mD Permeability and Limited Rock-Fluid and
Fluid-Fluid Sensitivity*

The case can be made that most formations may benefit
from a perfectly designed and executed UBD operations,
which is likely true. The unfortunate fact is that UBD
operations tend to be considerably more expensive than
conventional overbalanced drilling and by their nature may
be fraught with risks and problems. For normal "plain Jane"
type formations such as those described above it is likely that
well designed conventional overbalanced operations can be
designed and implemented yielding comparable or superior
results to a more expensive and risky underbalanced
operation.

Conclusions

Underbalanced drilling is a very complex process which
should not be designed and implemented on a gut feel basis,
or because it appears to be the trendy approach to a difficult
problem. When properly designed and executed UBD
provides a whole new approach to complex reservoir
management problems and may facilitate the economic
completion and exploitation of reserves unobtainable by any
other type of currently available technology. Detailed study
and design of the UBD process by a multifaceted reservoir
team is required along with acquisition of the necessary data
to ensure that the operation is viable for the reservoir under
consideration. If UBD is considered, the process must be
designed, implemented and monitored correctly. Failure to
carefully plan and design may result in the improper
application of UBD technology (in a potentially viable
situation), resulting in significant losses of capital and
production potential.

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