TECHNO-ECONOMIC STUDY ON UNDERBALANCED AND OVERBALANCED DRILLING

FINAL DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENT

FOR

Bachelor of Technology

GAS ENGINEERING
(2004-2008)

By

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Dehradun

2008

UNIVERSITY OF PETROLEUM & ENERGY STUDIES
(ISO 9001:2000 Certified)

CERTIFICATE

This is to certify that the project report on *"TECHNO-ECONOMIC STUDY ON UNDERBALANCED AND OVERBALANCED DRILLING"* submitted to University of Petroleum & Energy Studies, Dehradun, by ***Ms K J SUDHARSHANA*** in partial fulfillment of the requirement for the award of the Degree of **Bachelor of Technology** in **Gas Engineering (Academic Session 2004-2008)** is a bonafide work carried out by her under my supervision and guidance.

This work has not been submitted anywhere else for any other degree or diploma.

This work is deemed good and satisfactory.

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ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude to Mr. C K Jain, for his able guidance and support in making this Progress Report of the Final Dissertation a successful one.

I am thankful to the University Of Petroleum and Energy Studies for providing me an opportunity to pursue my Major Project and for providing me sufficient help whenever I needed.

I thank all my batchmates for the help extended by them to me. I would like to add that this report is an outcome of cooperation of all the faculty members at UPES and my batchmates at B.Tech (Gas Engineering), 2004-2008 batch.

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B.Tech (Gas Engineering)- VIII th Semester,

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May 12 , 2008

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SUMMARY

Summary

Underbalanced drilling, or UBD, is a procedure used to drill oil and gas wells where the pressure in the wellbore is kept lower than the fluid pressure in the formation being drilled. As the well is being drilled, formation fluid flows into the wellbore and up to the surface.

This is the opposite of the usual situation, where the wellbore is kept at a pressure above the formation to prevent formation fluid entering the well. In such a conventional "overbalanced" well, the invasion of fluid is considered a kick, and if the well is not shut-in it can lead to a blowout, a dangerous situation.

In underbalanced drilling, however, there is a "rotating head" at the surface - essentially a seal that diverts produced fluids to a separator while allowing the drill string to continue rotating.

If the formation pressure is relatively high, using a lower density mud will reduce the well bore pressure below the pore pressure of the formation. More commonly, inert gas is injected into the drilling mud to reduce its equivalent density and hence its hydrostatic force throughout the well depth. This gas is commonly nitrogen, as it is non-combustible and readily available, but air, reduced oxygen air, processed flue gas and natural gas have all been used in this fashion.

Underbalanced drilling is usually more expensive than conventional drilling, and has safety issues of its own. This is true when combustible and corrosive gasses like processed flue gas and oxygen are injected into the drilling mud to lower its density. Drilling underbalanced may be pointless from a formation damage standpoint if the underbalanced condition can not be maintained - which can be difficult when the drillstring needs to be removed to change a bit, or if the flow must stop in order to allow mud pulse telemetry to be sent.

RESEARCH OBJECTIVES

OBJECTIVES

1) To give an overview of Underbalanced drilling,

2) To discuss the Technical Indicators and Contra-Indicators,

3) To discuss the economic Indicators and Contra-Indicators,

4) To elaborate upon the benefits of Reservoir Characterization,

5) To compare Underbalanced drilling with Conventional Drilling,

6) To arrive at an logical conclusion as to why Underbalanced drilling should be considered,

Chapter 1 :

UNDERBALANCED DRILLING OVERVIEW

1. UNDERBALANCED DRILLING OVERVIEW

INTRODUCTION

Conventional drilling practice calls for maintaining the hydrostatic pressure of the drilling fluid between the formation's pore pressure and its fracture pressure. The drilling fluid is continuously circulated within the well bore to control the formation fluids and transport cuttings to the surface. It also works as a stabilizing agent within the well bore, and lubricates and cools the drill bit. The fluid is either a water-based or oil-based liquid that varies from 7.8 to 19 pounds per gallon, and contains a variety of solid and liquid products to impart density, fluid loss characteristics and rheological properties.

The conventional practice described above has long been recognized as the safest method for drilling a well. It does, however, have drawbacks. Since the drilling fluid pressure is higher than the natural formation pressure, fluid invasion frequently occurs, causing permeability damage to the formation. This damage is mainly caused by washout or physical blockage by the intrusion of fluids and/or solids into the formation structure [1].

Underbalanced drilling is a drilling method which reduces the hydrostatic pressure of the drilling fluid column so that the wellbore pressure is less than the pressure of the formation. The use of underbalanced drilling methods is improving production rates and the ultimate recovery of oil and gas reserves in many of the areas where hydrocarbon reservoirs are being found today[1], including North America, the North Sea, the Middle East, and Indonesia. The potential exists for underbalanced drilling to improve field economics by increasing production rates and improving access to oil and gas reserves.

Underbalanced drilling is considered one of the more exciting recent developments in drilling technology. Initially used to exploit lower quality reserves, underbalanced drilling has also proven to be an economical and viable method for drilling in low pressure and depleted or clay-rich reservoirs. As opposed to conventional drilling, hydrocarbon flow rates can be recorded during the process making it easier for operators to accurately identify pay intervals and stop drilling operations as soon as target zones are penetrated, thereby minimizing formation damage caused by exposure to drilling fluids.

HISTORY OF UNDERBALANCED DRILLING

The concept of drilling with low pressure circulating fluid was first patented in the United States in 1866. Early applications used compressed air to drill the hole. As the technology evolved over the years, gas internal systems with stable foams and aerated fluids were introduced for specific drilling conditions

The technique called ***flow drilling*** was first developed in South Texas, and became very popular worldwide with early successful applications in Southern Canada, Australia and China. It was primarily used for re-development of fields where depleted pressure was an important concern.

During the 1990's, underbalanced drilling was successfully applied in onshore and offshore drilling operations throughout Europe. Early techniques developed by Angel (1957) and, Moore and Cole (1965) tried to predict the volume of air or gas required to adequately clean the air-drilled hole. There were also several attempts published in the literature to develop a systematic design procedure for estimating wellbore hydraulics in underbalanced drilling applications. Currently, underbalanced drilling is the most exciting development in the area of drilling engineering. Together with horizontal and multi-lateral drilling techniques, it holds tremendous value for drilling more cost-effective wells.

UNDERBALANCED DRILLING TECHNIQUES

Underbalanced drilling techniques are classified according to density of the fluids used in the process. Typical fluid densities range from near 0 to 7 pounds per gallon.

In fresh-water applications, the density of the circulating fluid can be reduced by nitrogen gas injection. This reduced density helps to achieve a bottom hole circulating pressure that is less than that of the formation pressure. Even conventional liquids can provide underbalanced conditions with proper density control of the drilling fluid. On the other hand, it is also possible for a low-density fluid to cause overbalance due to the frictional pressure drop.

Underbalanced drilling has proved to be an economical method for drilling in depleted/low pressure reservoirs. Since it is possible to record production during drilling, operators can easily and accurately identify inflow mechanisms and pay intervals, and cease drilling operation as soon as the target zones are identified.

One method of controlling the bottomhole pressure (BHP) is to use a choke at the surface. BHP is controlled by opening or closing the choke to lower or raise the standpipe pressure. Since the speed of a pressure wave through a static fluid column is equal to the speed of sound in the same medium, a lag time is experienced until the choking action at the surfaces reaches bottomhole. Estimating the lag time in a single-phase system is relatively easy, whereas the same calculation in multi-phase systems can be quite complicated.

Instead of using a choke, the BHP can also be controlled by adjusting the Equivalent Circulating Density (ECD). This technique essentially creates an increasing fluid density gradient between the surface and the bottomhole. If the casing is set at a shallower depth, ECD is preferred over choke pressure control. Since ECD is a function of flow, underbalanced conditions should be preserved by controlling the hydrostatic head when flow stops during connections[2].

The greater the flow resistance, the higher ECD will be. On the other hand, it can also create an opposing condition when pipe is pulled out of the hole, causing a swabbing effect.

Chapter 2 :

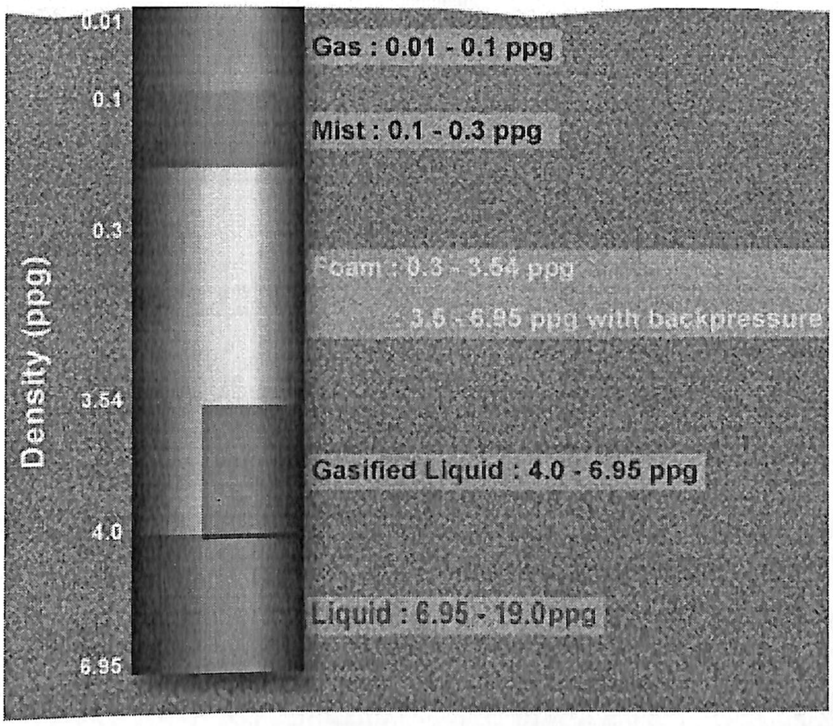
UNDERBALANCED DRILLING FLUIDS

2. UNDERBALANCED DRILLING FLUIDS

There are three primary types of fluids used in underbalanced drilling operations:

- Gaseous (Compressible)
- Two-phase
- Liquid (Incompressible)

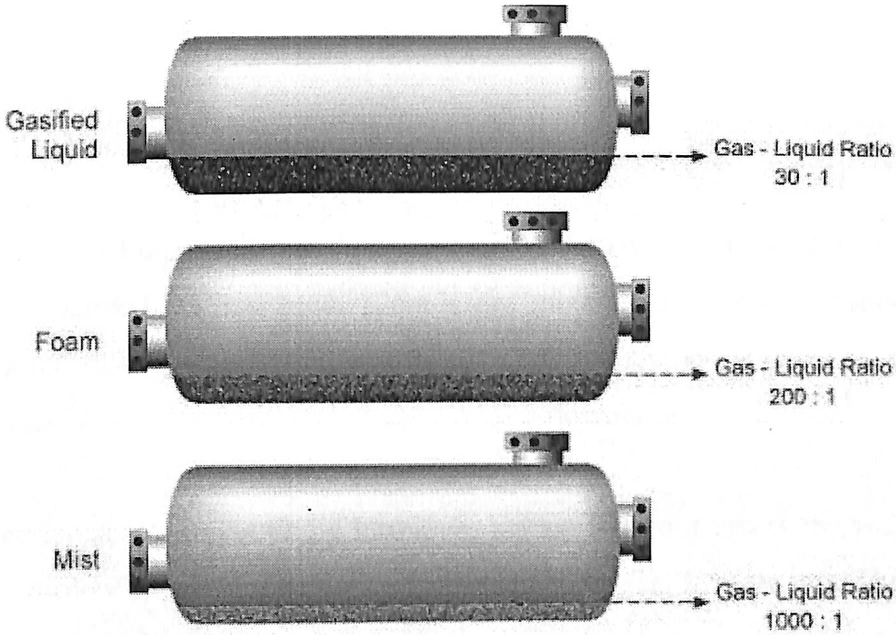
The fluid type is dictated by the boundary conditions of the drilling system. Typically, the boundary conditions are defined by bottomhole flowing pressure, formation fracture pressure, borehole collapse pressure and formation pore pressure. The density range of various drilling fluids is summarized in the following diagram[2].



Two different measures are used to define the type of fluid system:

- Ratio, the gas-to-liquid volume at standard conditions.
- Quality, the ratio of gas volume to liquid volume at hole conditions

Gas-to-liquid ratios of various drilling fluid systems are shown in the following figure:



GASEOUS DRILLING FLUID

The oldest and most basic technique is dry air drilling, which involves pumping air down the drill string and up through the annulus. A rotating wellhead between the blowout preventer and rotary table is used to divert the returns. The cuttings are sent away from the rig via a discharge pipe, and a water spray is used to kill dust at the outlet. A flame is used to burn any returning hydrocarbons. Nitrogen is another common drilling fluid. Other inert gases are too expensive to be used in this process. A typical method to generate N_2 is to use membrane type filters that extract the N_2 from the air stream before it is pumped into the wellbore. Natural gas is also a drilling fluid option, since it is easily available from pipelines. It can directly be used without the help of compressors[2]. More information on nitrogen and natural gas drilling is provided under the "Underbalanced Drilling Methods" subtopic.

Circulating pressure and hole cleanup are dependent on each other. More cuttings in the well bore cause higher down hole pressures. Angel's method provides some guidelines regarding air flow rates required for hole cleaning. His charts are still widely used. According to these charts, 3000 ft/min is the minimum velocity for effective cutting transport.

2.2 TWO PHASE DRILLING FLUID

Two-phase drilling fluids, or ***lightened drilling fluids,*** consist of either foam-type fluids or aerated drilling mud. Liquids are mixed with gas to achieve a required circulating fluid density. The equation of state method is used to predict fluid properties at downhole conditions.

A pump is used to inject liquid into a gas stream before it enters the well. The small liquid droplets affect the behavior of the circulating gas. If more liquids (2.5% -25%) are introduced, then a foam phase is generated in which the liquid forms a continuous structure, entrapping the gas bubbles inside.

Once the liquid volume exceeds 25%, we no longer have a foam structure. This next level comprises aerated drilling muds (fresh water, brine, diesel or crude oil). Parasite strings are typically used to introduce gas into the circulating liquid stream. A parasite string is an external flow path (possibly coiled tubing), which is run and cemented outside of the casing[2].

Since gas and liquid compressibility values differ significantly from each other as pressure and temperature changes, the liquid fraction changes as well. Frictional pressure drops are controlled mainly by the flow regime, flow rate, fluid properties and flow geometry. Therefore, phase behavior is a very important component in underbalanced drilling models. Many investigators, including a special institute at the University of Tulsa, have extensively analyzed two-phase flow patterns and regimes. Some of the most common two-phase flow regimes are:

- Bubble flow
- Annular dispersed flow
- Stratified or laminar flow
- Plug or churn flow
- Slug flow

2.3 LIQUID DRILLING FLUID

Since formation pressure is usually larger than the hydrostatic pressure of fresh water or saline water, conventional drilling fluids might also provide underbalanced conditions. Even if the drilling fluid density exceeds the formation pore gradient, fluid loss into a formation can cause reduced pressure regions within the wellbore, thus allowing formation fluids to flow in.

Chapter 3 :

BENEFITS AND LIMITATION OF UNDERBALANCED DRILLING

3. BENEFITS AND LIMITATIONS OF UNDERBALANCED DRILLING

3.1 ADVANTAGES

Underbalanced drilling offers a number of important benefits:

- Maintaining wellbore pressure below the reservoir pressure allows reservoir fluids to enter the wellbore, thus avoiding formation damage. Since significant formation damage is avoided, the stimulation requirements during well completion are also reduced, leading to considerable savings.
- During underbalanced drilling there is no physical mechanism to force drilling fluid into the formation drilled. Therefore, lost circulation is kept to a minimum when fractured or high permeability zones are encountered.
- Drilling Underbalanced can help in detecting potential hydrocarbon zones, even identifying zones that would have been bypassed with conventional drilling methods.
- Due to the decreased pressure at the bit head, UBD operations demonstrate superior penetration rates compared to conventional drilling techniques. Along with reduced drilling times, an increase in bit life is typically reported.
- Since there is no filter cake around the wellbore wall, the chances of differential sticking are also reduced.
- Since conventional drilling fluids are not used in Underbalanced drilling applications, there is no need to worry about disposing potentially hazardous drilling mud.

A combination of all these factors can significantly improve the economics of drilling a well. UBD is often preferred if it reduces formation damage and hole problems, and reduces the cost of stimulation in fractured or moderate/high permeability formations. Moreover, with good mud logging and drilling records, UBD can provide valuable Formation Evaluation data.

3.2 DISADVANTAGES

Underbalanced drilling also has disadvantages that can prove detrimental to the outcome of the drilling process:

- There is a higher risk of blowout, fire or explosion.
- Underbalanced drilling is still an expensive technology. Depending on the drilling fluid used, the cost can be significant, particularly for extended reach horizontal wells.
- It is not always possible to maintain a continuously underbalanced condition. Since there is not a filter cake around the wellbore, any instantaneous pulse of overbalance might cause severe damage to the unprotected formation.
- UBD has its own unique damage mechanisms, such as surface damage of the formation due the lack of heat conduction capacity of underbalanced drilling fluids.
- It is more complicated to model and predict the behavior of compressible drilling fluids.

Chapter 4 :
HOT CLEANING CONSIDERATION

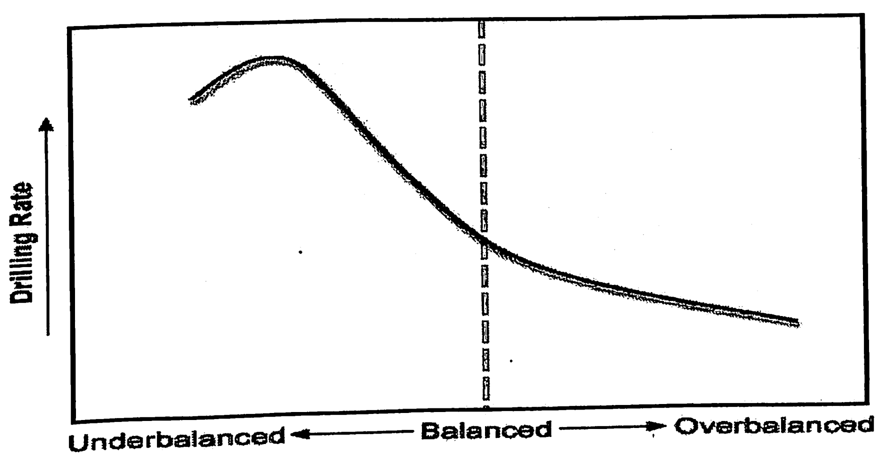
4. HOT CLEANING CONSIDERATIONS

Decreased bottom hole pressure typically causes higher penetration rates. However, higher penetration rates can increase the circulating bottom hole pressure and bring the well back to overbalanced conditions. Moreover, due to the annular fluid segregation, there is an increased risk that the wellbore will pack-off, resulting in stuck pipe. In this situation, gas tends to rise while the liquid settles to the bottom of the hole. This is a major cause of increased bottom hole pressures because of the increased fluid density at the sand face.

Large cutting volumes generated by high penetration rates are also difficult to remove. Therefore, penetration rates should be carefully adjusted to ensure sufficient hole cleaning and slug removal.

Inadequate liquid flow rates can cause sticky-hole conditions that result in differential sticking. A decrease in ROP would therefore be needed for the cuttings to be transferred to the surface. A viscosified aqueous phase is an important factor in achieving better ROP.

When drilling with foam and mist, hole cleaning efficiency reaches a limit after a certain level of underbalance, and the drilling rate starts to decrease as illustrated in the following figure.



Chapter 5 :

LIMITING TECHNICAL FACTORS

5. LIMITING TECHNICAL FACTORS

Major technical factors that restrict the application of underbalanced drilling techniques are listed as follows:

- Reduced wellbore pressure gradients can cause hole stability problems
- Formation of mud rings can block air flow, leading to downhole fires
- Water causes cuttings to accumulate, possibly causing the drill string to stick. If aerated mud is used rather than air, differential underbalance can be reduced.
- HC's and air often mix to achieve a flammable range. With a small spark, which can be generated by the contact between the drill string and hard minerals, the risk of fire increases.
- Stable foam condition is not easy to achieve.

Depending on the drilling site location, logistical and economical constraints can be substantial. Similarly, the need for specialized drilling equipment can also render underbalanced operations uneconomical.

"Even though the cost of drilling underbalanced could be more expensive than conventional overbalanced drilling, due to the increased ROP and reduced formation damage, it often turns out to be the more cost-effective drilling technique".

Chapter 6:

UNDERBALANCED DRILLING WITH GAS

6. UNDERBALANCED DRILLING WITH GAS

Gases used for underbalanced drilling include air, nitrogen, CO_2 or natural gas. When natural gas is available, it can be the most cost-effective method to achieve an underbalanced condition because it can be recovered and re-injected into the supply/sales line, but it is not always an option. Air injection drilling is common, but significant corrosion problems and the potential fora downhole fire or explosion are deterring factors.

In general, there is desire to minimize CO_2 emissions. Therefore, nitrogen has often become the medium of choice. Nitrogen is an appealing medium because of its relatively low generation cost, scale control, and low potential for downhole fire or explosion.

Injecting nitrogen through the drill pipe can be most cost effective when electromagnetic measurement-while-drilling (MWD) is used. Despite the added cost and time, parasite injection of nitrogen is the preferred method when electromagnetic MWD is not possible. Foams are more stable than aerated systems, but they are more costly.

CHAPTER 7:
CASE STUDY

7. CASE STUDY

Underbalanced drilling is a key technology and has been a high-growth activity in Shell since experimentation with the technique in the 1990s showed impressive results.

Underbalanced drilling (UBD) involves drilling with a column of fluid that exerts less counter pressure than the upward pressure from the oil, gas, water and condensate in the reservoir. This allows the hydrocarbons, water and condensates to be produced during drilling. To make the process safe, a closed circuit is created at the surface in which the hydrocarbons, reservoir water, cuttings and mud are separated[3].

Although UBD requires longer planning times and more topside equipment, it has several advantages over conventional methods in which the drilling fluid, or 'mud,' is heavier and maintains a strong downward pressure. With conventional, or 'overbalanced' methods, the heavy downward pressure can force large amounts of mud into fractured areas, which blocks the fluid flow paths. Both on-and offshore, UBD has demonstrated faster drilling times involving fewer drill bit changes and less likelihood of the drilling column jamming. Through less damage to the reservoir, UBD has shown improved flows of oil and gas to the well. UBD also enables real-time analysis of the borehole as it is drilled metre by metre, using a variety of data sent to the surface[4].

Shell deploys UBD to tap resources previously considered unrecoverable, such as depleted fields or low-permeability reservoirs in sandstones or carbonates where flow can easily be impaired using conventional drilling.

Shell has had great success with UBD, once considered a difficult and unsafe method,. Shell and other operators have actually demonstrated higher safety levels for UBD compared with conventional drilling. Shell has adopted the technology with great success in Abu Dhabi, Egypt, Nigeria, Oman and Syria.

Chapter 8 :

METHODS FOR OPTIMIZING DRILLING-HALLIBURTON

8. METHODS FOR OPTIMISING DRILLING- Halliburton

Introduction

The difficulties experienced when using conventional overbalanced drilling (OBD) methods have encouraged operators to seek other techniques. Two such techniques are underbalanced drilling (UBD) and managed pressure drilling (MPD), since both have shown success in optimising the drilling process. These two methods, if applied properly and in the appropriate circumstances, also benefit the reservoir when compared with conventional overbalanced techniques.

8.2 Background

UBD was initially adopted to resolve drilling problems, but it soon became evident that this technique could also minimize reservoir damage. As originally conceived, UBD included techniques that were fully Underbalanced with influx to the surface, as well as methods called 'low-head' and 'at-balance' drilling in which the bottom hole pressure was kept marginally above or approximately equal to the reservoir pressure. These techniques later became designated by the term MPD[5].

This terminology was eventually adopted by the International Association of Drilling Contractors (IADC) and MPD became a separate designation from UBD. In spite of its many benefits, UBD has not been embraced by the industry as widely or as readily as might have been expected. This reluctance has been due in part to additional equipment rental costs compared with conventional drilling, and in some cases regulations limit flaring or production while drilling.

Moreover, there can be resistance to new technologies as they require additional effort to learn and implement, and there is a perceived risk of failure when implementing new technologies compared with using more familiar methods.

8.3 Definitions

In 1994, the Alberta Energy Utilities Board Interim Directive defined UBD operations as follows: "When the hydrostatic head of a drilling fluid is intentionally designed to be lower than the pressure in the formations being drilled, the operation is considered Underbalanced drilling."

More recently, the IADC has defined MPD as "an adaptive drilling process used to precisely control the annular profile throughout the wellbore. The objectives are to ascertain the downhole pressure-environment limits and to manage the annular-pressure profile accordingly."

Some debate still remains in the industry as to what constitutes UBD and MPD and whether one is a subset of the other. Many would agree that all drilling – from conventional overbalanced to foam or air – can be considered a form of 'managed pressure' drilling, as the pressure must be controlled or 'managed' for safe drilling.

Therefore, MPD may be too vague a term to describe exactly where it is applied in practice, and the expression can cause confusion among those new to the industry[5].

If one accepts UBD and MPD as separate entities, a pragmatic approach may be to define where each is primarily used and for what purpose.

Exceptions will always exist; however, this article proposes that the differentiation between UBD and MPD be made based on whether the target bottomhole circulating pressure is intentionally maintained below the pore pressure throughout the open hole section (UBD), or equal to or marginally above pore pressure for all or most of the open hole section (MPD). An added proviso is that the objective of MPD is to preclude influx from the formation during the drilling operation, while the opposite occurs with UBD.

Each technique has its place, and the best applicable solution will depend on the problems anticipated. MPD cannot match UBD in terms of minimizing formation damage, allowing characterization of the reservoir or identifying productive zones that were not evident when using OBD; however, when the objective is to mitigate drilling problems, MPD can often be as effective as UBD, with the added advantage of being more economically viable. MPD is also preferable where wellbore instability is a concern, where there are safety concerns due to high H_2S release rates or where there are regulations prohibiting flaring or production while drilling. Both techniques have been applied in many types of formations containing different types of reservoir fluids and wells and in different hole sizes.

However, these criteria are not inherent limitations; rather, it is the formation pressures, stability, production potential and other factors, when evaluated from a technical and economic standpoint, that determine whether a candidate is a good prospect.

8.4 Comparison

MPD is used primarily to resolve drilling-related problems, although some reservoir benefits also may be achieved. This is not surprising, as any effort to decrease the degree of overbalance, and thus reduce the impact of drilling fluid on virgin formations, will usually result in some positive reservoir benefits. UBD, on the other hand, has long been employed to provide solutions to both drilling- and Reservoir-related problems.

MPD is often seen as easier to apply compared with full UBD operations. In non-reservoir sections, MPD design requirements often determine that a simpler equipment package will satisfy safety considerations for the well. The day rate would therefore be reduced compared with using full underbalance.

Equipment requirements for both operations vary depending on the design parameters of the project. In many instances, the same equipment set-up will be necessary for both UBD and MPD methods. The distinguishing difference is that for an MPD set-up, fluid influx is not typically expected during drilling; instead, it is used as a contingency measure or when a higher pressure zone exists that will produce to the remainder of the openhole section while the system is overbalanced. When the margins between pore and fracture pressure are very narrow, some level of automation has been sought in MPD to help to provide quick response to changes in downhole conditions.

While the vast majority of MPD operations – where the drilling margin is wide – will not require such 'fine' control, in some sectors where the pressure margin is narrow this degree of control will be beneficial when it is implemented with sufficient redundancy, safety and system controls in place. Eventually, as the MPD system proves reliable, it could also be utilised to enhance control of the target bottomhole pressure during UBD operations.

Addressing non-productive time (NPT) is a major focus for both MPD and UBD. NPT associated with kicks, wellbore breathing and lost circulation will have an immediate impact on rig time and its associated cost, and can also lead to additional costs associated with lost mud, lost circulation materials, additional casing string(s), stuck pipes and unplanned sidetracks. Any of these can directly affect a project's financial viability.

An added benefit of MPD and UBD has been an improvement in safety due to the more detailed planning and procedures required for their implementation. These systems allow for readily identifiable influxes in a controlled environment compared with conventional operations, which is of particular benefit for MPD in high-pressure, high-temperature (HPHT) wells.

Some UBD projects have not realised the reservoir production gains that were expected and this has often resulted in a reduced interest in using UBD. However, when reviewing the data from many wells, it becomes evident that one of the reasons that improvement did not meet expectations is that, although many wells have been classified as UBD, in reality underbalanced conditions were not maintained – some portion of the drilling was underbalanced, but overbalanced conditions often occurred or were intentionally used for tripping and/or completing the well.

This reduces or even eliminates any productivity gains from UBD, so in many instances appears that UBD has had little or no impact on reduction of formation damage and improved productivity. A key to productivity improvement is the mitigation of formation damage throughout the drilling and completion phases.

An additional reservoir-related benefit of UBD that should not be overlooked when compared it with MPD and OBD is the opportunity it provides for reservoir appraisal. It is possible to conduct comprehensive reservoir evaluation (well testing) during drilling via a properly executed UBD job that has been designed for reservoir fluid inflow throughout, along with proper equipment, metering and data acquisition.

The acquired data are integrated and used in reservoir simulators designed for the UBD process to estimate permeability, reservoir extent (if there is sufficient time to see this response), reservoir pressure, point of information (PI) or fracture properties of the zone drilled.

8.5 Conclusion

Technical specialists gauge a well's success in different ways. Drilling specialists view a well as successful if it reaches target at or below the dry-hole Authorization for Expenditure (AFE).

Geology and reservoir specialists classify a well as a success if valuable information about the drilled formations is obtained and these formations are productive. The asset team/manager wants the well to provide the information required, be highly productive and be drilled under budget.

When properly implemented, UBD and MPD have proved that they can satisfy all these drivers. Both can address drilling problems and reduce the NPT typically associated with conventional drilling and, where the primary drivers are reservoir related, UBD is the best option.

However, one should not choose one method over the other solely based on subjective considerations; the technical and economic comparison of all solutions should be performed, and a decision to 'do what's best for the well' should be taken depending on the merits of each technique.

Chapter 9 :

UNDERBALANCED DRILLING-A RESERVOIR FOCUS

9. UNDERBALANCED DRILLING- A RESERVOIR FOCUS

9.1 INTRODUCTION

Most everyone has heard about the successes of underbalanced drilling (UBD) in North America with the proven benefits of increased ROP, reduced formation damage, eliminated or reduced lost circulation and differential sticking[6].

In underbalanced drilling, the formation pressure is greater than the hydrostatic pressure. This allows hydrocarbons to flow into the wellbore during drilling while preventing drilling fluids from penetrating the producing formation.

Today, new techniques now offer an additional benefit providing true reservoir evaluation or "testing-while-drilling" capability. This provides invaluable reservoir data such as permeability and productivity index (PI) data while still drilling. By shortening the evaluation process and speeding up completion decisions, a considerable amount of rig time can be saved along with acceleration of production plans to make profits flow from the well sooner.

9.2 CANDIDATE SELECTION AND WELL PLANNING

The bad news is there is no such thing as a "cookbook recipe" for determining whether to drill a well underbalanced vs. conventional. At a first glance the drilling AFE will be notably higher, there will be additional resources, planning and training required, and a perceived safety risk will exist because the conventional primary barrier (hydrostatic mud column) no longer exists.

The good news is the technology has flourished in several areas around the world. This has been accomplished via safe and thorough planning, practical design, appropriate candidate selection and realistic view of overall economic feasibility. The objective of a successful UBD project is to add value in a specific well then apply that UBD technology to that field, resulting in increased production efficiencies, enhanced field value and reduced field development cost.

Once the UBD candidate is identified, preliminary flow modeling is performed to determine the fluid/gas requirements. From reservoir data, the modeling can predict the inflow during UB drilling, and surface equipment can be sized accordingly. HAZOPs must be done, drilling and emergency procedures must be written, safety cases and EHS documents must be created or modified. Rig interfacing and logistics planning are critical and integrating all people and equipment on location is a must for a successful operation.

9.3 WELL CONTROL

In terms of well control a concept shift with underbalanced drilling is necessary. The primary barrier of the hydrostatic fluid column when drilling conventional is replaced with the Rotating blowout preventer and surface equipment. The BOP Stack remains the secondary barrier[6].

9.4 WHY DRILL UNDERBALANCED?

There are many reasons why Operators are now using this technology:

- Reduce formation damage during the drilling and completion phase
- Reduce lost-circulation costs
- Reduce risk of lost-in-hole equipment
- Reduce rig time associated with sidetracking
- Increase reservoir recoverable reserves
- Performance enhancement tool by increasing ROP by 2 to 10 fold or more
- Increase value and reduce payout time by producing hydrocarbons while drilling
- Early Reservoir Evaluation
- Testing while Drilling
- Reservoir Fluid Samples
- Reservoir characterization while the bit is still on bottom

9.5 Good Candidates

- Mature / depleted / under-pressured reservoirs
- Naturally fractured sandstones and carbonates
- Tight gas sands
- Fluid sensitive formations
- Horizontal wells
- Heavy oil applications
- Many combinations of the above
- It is critical for Operators to establish and understand their objectives for drilling underbalanced.

9.6 Operator Experience

Many Operators have experienced what could only be described as "phenomenal" success from drilling underbalanced. Reservoir simulation and modeling that attempts to account for this is very difficult, and the only means of matching results is to introduce a negative skin (representative of a fractured well).

Chapter 10 :

ECONOMIC FACTORS-TECHNICAL REQUIREMENTS

10. ECONOMIC FACTORS- TECHNICAL REQUIREMENTS

10.1 Drilling Fluid Design

There is a popular misconception that "designer fluids" must be used in UBD. The fact is, any type of fluid can be used as long as it results in an equivalent circulating density (ECD), which is less than the reservoir pressure, thereby maintaining underbalanced conditions[7].

10.2 Equipment Design

Several equipment enhancements are providing the industry with the means of applying this technology in more challenging applications[7]. Key improvements are in the areas of four phase separation systems, automated controls, electronic safety systems, advanced data acquisition, rotating BOP advancements as well as modular equipment designed for offshore applications.

10.3 Four-Phase Separation Systems

The different phases of Fluid produced during underbalanced drilling present multiple problems. Newly designed equipment packages are able to efficiently handle the drill cuttings, oil, water, gas, and mud produced during underbalanced drilling.

These systems will handle up to 35,000 bpd fluids and 50 MMscfd gas and can operate in corrosive hydrogen sulfide environments. The two-stage design maximizes gas removal from drilling and produced fluids. A continuous fluid flush system ensures good solids separation and management. Vertical separator configurations also help to improve slugging handling capacity.

Additional enhancements include special design dual, adjustable, remote actuated 3" full opening drilling chokes.

10.4 Safety Systems

The oil & gas industry (outside of North America), in general, has been slow to embrace UBD technology, sometimes citing that additional safety systems need to be considered to ensure well control and safety of personnel.

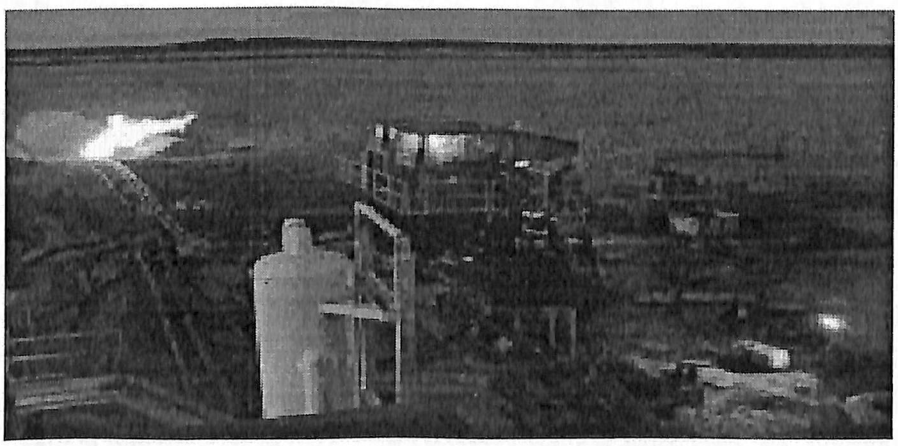
Newly developed safety systems include integrated PLC-based electronic Emergency Shut-Down (ESD) systems. These systems are designed to automatically close in and isolate the well in the event of upset conditions (ie: unexpected high pressures, fluid levels, line breaks, LEL or H2S detection, etc).

10.5 Advanced Data Acquisition System

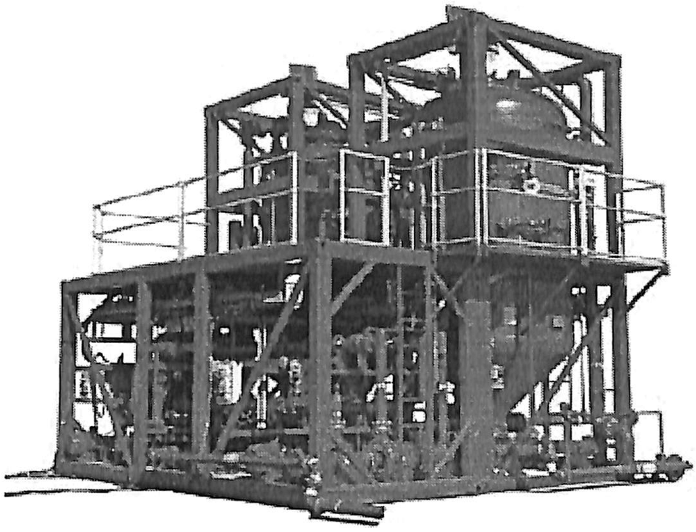
An advanced data acquisition system has been developed to gather, manage and store all relevant information at the rig site in real time. This data can also routinely be sent off-site, via satellite or land line to the Operator's office or can be setup to be viewed real-time via secure Internet connection.

10.6 Rotating BOP's

Rotating BOP's are used during Underbalanced Drilling to allow rotation of the drill pipe while the well is under pressure. Systems have been improved in recent years to the point that pressure can be contained to 5,000 psi while in static mode and 3000 psi during drilling operations and are built to same API specification as annular preventers.



Underbalance Drilling in the Australian Outback with 4 Phase Separator Package



New Design 2-stage, 4-phase separation system.

All of the above economical factors required for the technology success are cost incurring and hence significantly add on to the project economics. Thus, Underbalanced drilling is a cost intensive technology but in terms of the recovery achieved it is surely a wise proposal to be pursued.

Chapter 11 :

TECHNICAL AND ECONOMICAL FEASIBILITY STUDIES

11. TECHNICAL AND ECONOMICAL FEASIBILITY STUDIES

As a direct result of the experience, background, and research activities, Blade is able to conduct technical and economic feasibility studies, especially in the application of emerging technologies to oil field problems[7]. They have conducted several such studies, and our results speak for themselves in continued recommendation of this service by our growing client base. Among the recent and ongoing feasibility studies are:

- Feasibility of Underbalanced drilling in a highly-fractured granite formation
- Study on big bore completions in high-rate gas wells
- Feasibility of underbalanced drilling from an independent marine vessel
- Investigation of drilling and workover technologies in sub-hydrostatic pressure gas fields
- Feasibility of offshore thru-tubing drilling
- Feasibility of Coiled-Tubing underbalanced drilling in high rate producing wells
- Investigation of Coiled Tubing workovers in high-pressure, high temperature wells

Our feasibility studies derive the full benefit of our specialization in risk and reliability-based approaches, not just in the technical aspects, but also in economic evaluation.

All of the above studies conducted have proved Underbalanced drilling to be a very valid and economic proposal all around in many parts of the country[7]. But Underbalanced drilling has its own economic non-indicators.

Economic Contra-Indicators:

Underbalanced drilling is usually more expensive than conventional drilling, and has safety issues of its own. This is true when combustible and corrosive gasses like processed flue gas and oxygen are injected into the drilling mud to lower its density.

Drilling underbalanced may be pointless from a formation damage standpoint if the underbalanced condition can not be maintained - which can be difficult when the drillstring needs to be removed to change a bit, or if the flow must stop in order to allow mud pulse telemetry to be sent.

Information is frequently needed from the bottom of the well (knowledge of bottom hole pressure is very important in underbalanced drilling, as is information for geosteering if it is a deviated well). When gas is injected into drilling mud, standard mud pulse telemetry becomes impossible. "Killing" the well (making it overbalanced) may be necessary to send information, inducing formation damage. Underbalanced drilling also increases the chances of the wellbore collapsing in on itself.

There is a higher risk of blowout, fire or explosion.

Underbalanced drilling is still an expensive technology. Depending on the drilling fluid used, the cost can be significant, particularly for extended reach horizontal wells.

It is not always possible to maintain a continuously Underbalanced condition. Since there is not a filter cake around the wellbore, any instantaneous pulse of overbalance might cause severe damage to the unprotected formation.

UBD has its own unique damage mechanisms, such as surface damage of the formation due the lack of heat conduction capacity of Underbalanced drilling fluids.

It is more complicated to model and predict the behavior of compressible drilling fluids.

Economic Indicators:

Underbalanced drilling technology can save the industry millions of dollars by increasing the amount of recoverable oil within a shorter time frame.

Underbalanced drilling has proved to be an economical method for drilling in depleted/low pressure reservoirs. Since it is possible to record production during drilling, operators can easily and accurately identify inflow mechanisms and pay intervals, and cease drilling operation as soon as the target zones are identified[8].

It is a valuable method for minimizing formation invasion related problems. Because the majority of hydrocarbons today are found in existing fields with depleting pressures, or in complex and low quality reservoirs, the economical use of UBD becomes more and more popular.

A combination of all these factors can significantly improve the economics of drilling a well. UBD is often preferred if it reduces the formation damage and hole problems, and reduces the cost of stimulation in fractured or moderate/high permeability formations[8]. Moreover, with good mud logging and drilling records, UBD can provide valuable formation evaluation data.

Chapter 12 :

RESERVOIR CHARACTERIZATION DURING UNDERBALANCED DRILLING

12. RESERVOIR CHARACTERIZATION DURING UNDER BALANCED DRILLING

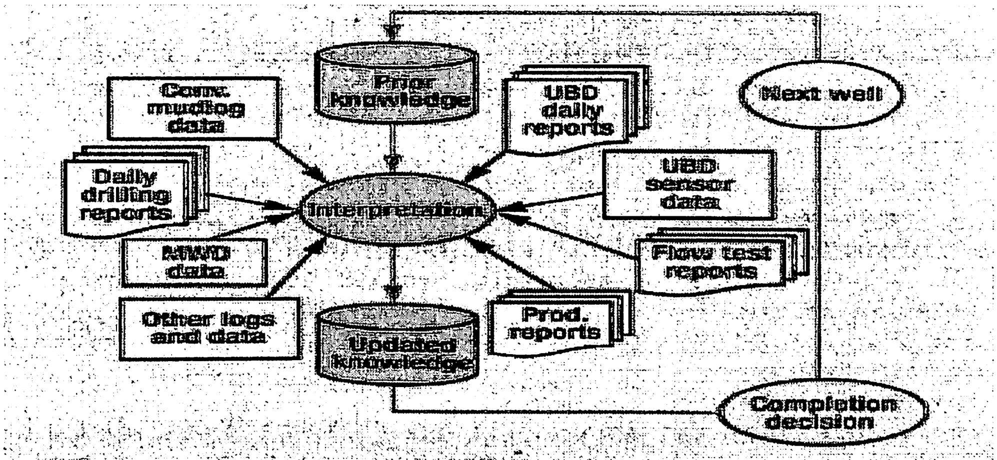


Fig. 1. Ideal Reservoir Characterization Process, showing all the inputs required for accurate interpretation.

Since 2002 when Shell introduce underbalanced drilling into Oman, Shell affiliate, Petroleum Development Oman (PDO), has had a continuous Underbalanced Drilling (UBD) campaign. Initially, improved oil production and lower unit total cost (UTC) were the primary drivers for PDO. However, while drilling the fourth well in rhe campaign, a water influx was encountered[9]. Evaluation of the inflow data revealed that the influx was through a conductive fracture. This information was a surprise to the asset team, because the reservoir was modeled as a homogenous unfractured reservoir.

The discovery of non-matrix reservoir behavior marked the start of the development of Underbalanced Drilling Reservoir Characterization (UBD RC) within PDO. Shell has previously recognized that UBD RC and improved productivity are now the key drivers for drilling UBD at PDO. UBD RC is the big step between defining rock properties and saturations, and understanding reservoir fluid movement.

UBD RC is used to answer two fundamental questions: "Does this well produce oil?" and "Where is the water coming from?”

Hundreds of documented cases have shown that wells drilled underbalanced result in significant production rates with, accelerated production, and greater recoverable reserves. Recent developments in reservoir modeling have led to the use of customised analytical models, which can predict influx potential, and permeability vs. depth.

This is not an easy task. The well is being analysed in a transient state while flowing, net pay is changing with drilled depth, varying pore pressures through different layers is very difficult to analyse and can include cross-flow which must be accounted for[9]. Additionally, lag-time corrections must be made to translate from surface to equivalent down hole rates.

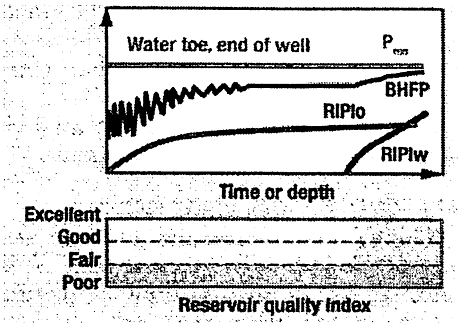


Fig. 3. Changes in reservoir quality and flow composition—effects on bottomhole flowing pressure.

Advanced Reservoir Modeling has attempted to incorporate all of the above complexities. After several years of study and multiple cases evaluated, it has been discovered that, with meticulous recording of underbalanced drilling parameters combined with execution of the model, useful reservoir information can be extracted.

An integral part of the system is to continually monitor and integrate injection rates, production rates, and bottom hole pressure as well as other reservoir parameters. The basic modeling process incorporates Darcy's traditional flow equation and filters out some of the abnormalities typically seen during Underbalanced Drilling Operations such as fluid slugging, cross-flow and transient effects.

The modeling then predicts permeability versus depth in a dynamic state as the formation is drilled. Monitoring reservoir flow and modeling performance on a foot-by-foot basis provides an assessment of the productivity potential of the well while drilling.

This process can be performed after drilling has been completed. Alternatively, the history matching process can be applied to the data stream as it is acquired in order to develop and update the reservoir model in "real time" (ie; while the bit is on bottom).

UBD defines rock properties, gives understanding of moveable fluid in the reservoir. From these data a curve is derived called "Rate Integral Productivity Index" (RIPI). RIPI is not a true productivity Index, in traditional well testing sense. It is comparison of changes in flow for each new meter drilled. Trends and changes in RIPI can be matched with petrophysical data to reveal a clearer view of the reservoir and its production behavior[10].

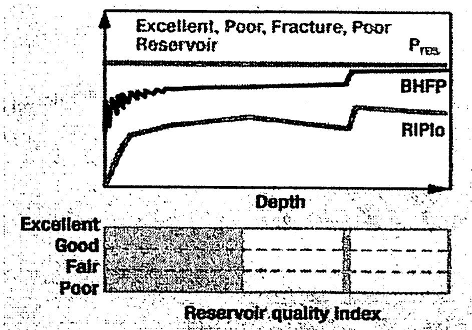


Fig. 2. Reservoir quality and an oil-bearing fracture—effects on bottomhole flowing pressure and RIPI.

Flow production rates, reservoir pressure, fluid composition and bottom hole circulating pressure can therefore identify non-contributing features (fractures etc) and high/low permeability features.

Advantages of UBD RC

- To know the PI of wells before production
- Identify contributing fractures that may of may not contain water
- Identify high productivity intervals
- Identify flushed zones that appear to have good saturations but produce only water
- Redefine resistivity that produces hydrocarbons

Formation damage during conventional drilling

Formation can be damaged during drilling in three ways

I. Mechanical formation damage: This includes the following:
    - Fines migration: fines migration is near well bore area due to rapid fall off in radial invasion velocity
    - Mud solid invasion occurs in open hole completion, high permeable formations, fractured formation and under extreme overbalanced pressure.

- Phase trap problems: These are subirreducibly saturated low permeability gas reservoirs.

II. Chemical formation damage: This happens due to interaction of filtrate from mud and rock, filtrate and reservoir fluid interaction etc

III. Biological formation damage: Bacterial generation due to degradation of organic chemicals can lead to plugging issues, corrosion issues and toxicity issues[10].

Applicability of UBD

- Highly pressure depleted formations
- Fractured, vugular formations exhibiting drilling problems and lost circulation
- Formation damage- sensitive formation
- Subirreducibily- saturated formations
- Formations exhibiting very low rate of penetration with overbalanced drilling

Less favorable for UBD

- Formations dominated by matrix low permeability rock
- Combination of very high pressure and high permeability zones
- High H_2S content in reservoir fluids
- Variation in zonal pressures
- Poor mechanical stability of target zone
- Unknown reservoir pressure
- Near dew point rich gas system
- Normally-pressured, average type reservoirs for which better designed conventional technology may be affected with less expense and risk

Potential problems with UBD

- Safety and control system

- Well bore stability
- Increased cost/ logistics
- Potential severe formation damage-if not properly executed
- Hole cleaning concerns
- Completion and work over issues

Common causes for loses of UB Pressure

- During pipe connection
- Conventional MWD operations
- Kill jobs/ Bit trips
- Localized depletion
- Variable/ multiple pressure zones
- Frictional flow effects
- Poor hole cleaning

Conclusion for UBD RC:

UBD RC is a newtool that has been developed and implemented by Shell and PD~ to improve all aspects of planning, drilling, completing and producing a well[10]. The benefits Of UBD RC include:

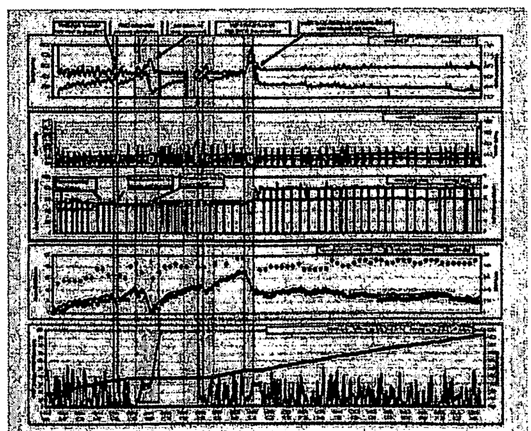


Fig. 6. Drilling Composite Plot: From top to bottom, Plot 1 is bottomhole circulating pressure and Rate Integral PI; Plot 2 is standpipe pressure and wellhead pressure; Plot 3 is liquid and gas Injection rates; Plot 4 is cumulative gains and fluid weight out; and Plot 5 is ROP, measured hole depth and off-bottom depth.

- Real-time identification, location of contributing fractures and features
- Real-time identification of fluids and fluid type produced from different reservoir segments
- Real-time identification of high permeability zones
- Provision of information to enable the well path to be steered, based on fluid returns or non-returns

- Real-time correlation to LWD data
- Enable the entire well planning team to collaborate more effectively
- Updating reservoir models for fractures and flow characteristics
- Real-time UBD RC is complementary to mechanical profile control for the decision-making process and placement of mechanical profile control equipment. Ultimate recovery is improved by identifying and isolating fracture flow to the onset of water production. UBD RC has its limitations, but technical developments in data acquisition will help improve these results.

Shell and PD~ has already realized considerable value in UBD RC, even though the development is in its infancy. The value to PD~ is that it answers the questions most important to an oil producing asset-"Does this well produce oil?" and "Where is the water coming from?" Armed with the answers to these questions, corrective action can be taken.

Chapter 13 :
RESERVE OPTIMIZATION

13. RESERVE OPTIMIZATION

The ability to analyze reservoir characteristics during under-balanced opera-tions increases the opportunities to minimize reservoir damage, determine reservoir potential, and maximize production. Planning, data-gathering capabilities, and a complete understanding of underbalanced drilling dynamics are critical to success.

Several record-setting projects in the past 18 months have resulted in lowered costs and increased production, while new technologies have shed light on the value of pressure control in the pay interval, particularly on wells with prolific production potential.

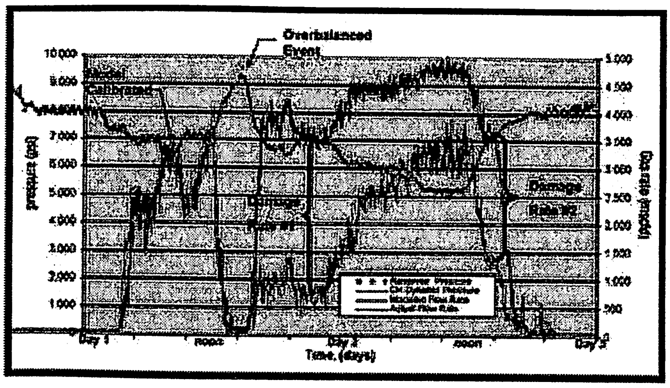


Fig: Negative effect of an overbalanced event in a generalized example

To be assured of true underbalanced drilling throughout the pay intervals, it is essential to use fit-for-purpose equipment, data acquisition, data management, and wellbore and reservoir modeling simulators to provide analysis and control of the activity downhole at the pay interval[10]. Figure 1 reflects a composite of field cases depicted by the reservoir analysis from this kind of capability.

As pay is intersected in an underbalanced environment, the service produces a quantified reservoir characterization. As sometimes happens, an unplanned pressure event throws the system into overbalance, even for a relatively short period of time. After underbalanced conditions are returned, the damage to the reservoir can be determined. In Damage Rate No. 1, the analysis determines a 5-fold reduction in rate. After an effort to "blow out the damage" with greater drawdown pressures, Damage Rate No. 2 reflects 2 1/2-fold reduction[10]. The most significant observation is that for this case the damaged formation never cleans up to original rates over the observed period. When modeled, the information from the result and the resulting loss of productivity is quantified, value giving the operator an evaluation of the production lost because of overbalance. Typically, the loss of production over the life of the well exceeds the cost of the analysis.

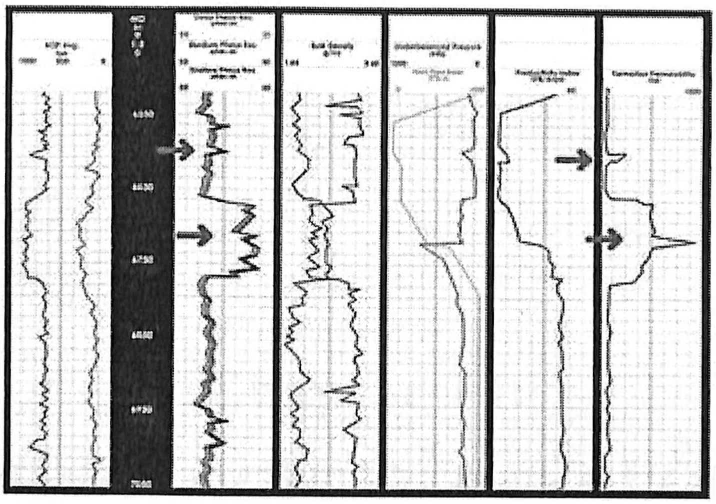


Fig: Reservoirs previously deemed non-commercial

Chapter 14:
NEW TECHNOLOGICAL DEVELOPMENTS

14. NEW TECHNOLOGICAL DEVELOPMENTS

Several key emerging technologies are evolving which will undoubtedly push this technology into the mainstream in the international arena:

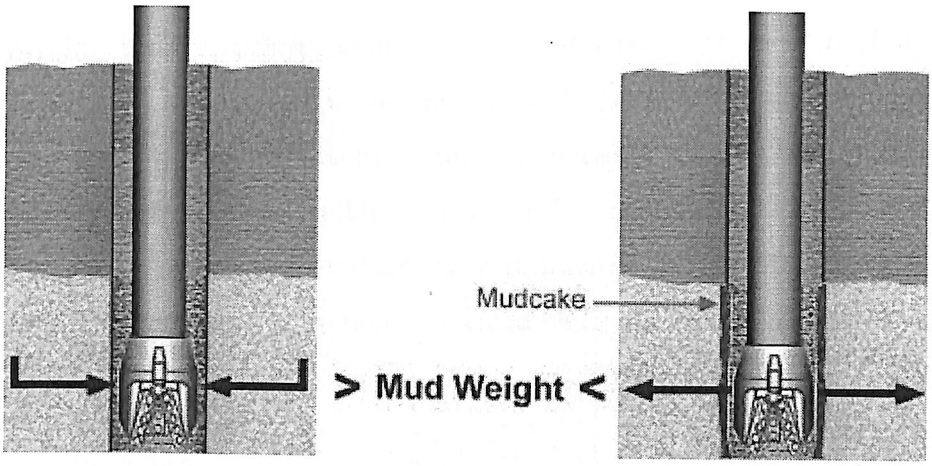
1) Continuous Circulation System
2) Quick Trip Valve
3) Transient Flow Modeling
4) Reservoir Characterisation While Drilling Underbalanced
5) Telemetry Systems
6) Advanced Separation/Safety Systems
7) Integrated UBD Rig
8) Offshore Technologies (Floating Rig)
9) Sonic Gas Measurement Device

Chapter 15 :

TECHNOLOGY COMPARISON OF UBD AND OBD

15. TECHNOLOGY COMPARISON OF UBD AND OBD

Underbalanced drilling (UBD) is defined as the practice of drilling a well with the wellbore fluid gradient less than the natural formation gradient. It differs from conventional drilling in that the bottomhole circulating pressure is lower than the formation pressure, thereby permitting the well to flow while drilling proceeds[11].



Besides minimizing lost circulation and increasing the penetration rate, this technique has a widely recognized benefit of minimizing the damage caused by invasion of drilling fluid into the formation. In many UBD applications, additional benefits are seen due to reduction in drilling time, increased bit life, and early detection and dynamic testing of productive intervals while drilling. It is critical to keep the well underbalanced at all times, if formation damage is to be minimized.

Underbalanced drilling technology is a valuable method for minimizing formation invasion related problems[11]. Because the majority of hydrocarbons today are found in existing fields with depleting pressures, or in complex and low quality reservoirs, the economical use of UBD becomes more and more popular.

Most of the underbalanced drilling applications today are conducted through the use of coiled tubing systems. Forty percent of all the onshore wells drilled in the year 2000 were conducted through underbalanced conditions. Joint industry projects currently underway off the coast of Brazil will likely change the conventional drilling practices in offshore applications.

On the other hand, Conventional drilling requires the hydrostatic pressure of the drilling fluid to remain above the formation's pore pressure and below its fracture pressure.

The drilling fluid circulates continuously in the wellbore to control the formation fluids and bring the cuttings to the surface while helping to stabilize the wellbore and lubricate the drill bit. Problems with conventional drilling methods include lost circulation, differential sticking, low drilling rates and formation damage. Underbalanced drilling can reduce these problems. Even though it is initially more costly, the rate of return from underbalanced wells can be significantly higher.

Chapter 16 :

POTENTIAL OF UBD AND OBD

16. POTENTIAL OF UBD AND OBD

When a client chooses to drill underbalanced, pre-job planning and front-end engineering design are paramount for a safe and successful project. Underbalanced drilling operations are inherently complex and require additional equipment; hence the AFE will be greater than a conventional drilling scenario. However, there also exists a real potential for great rewards with underbalanced drilling via:

- Reduced/Eliminated Drilling Problems:
  - Reduction in drilling costs due to fewer drilling days as a result of increased rate of penetration,
  - Lower costs due to less drilling fluid losses,
  - Decreased loss time due to differential sticking and
  - Fewer problems associated with loss circulation
- Reservoir Exploitation:
  - Increased productivity of a well that is thought to have the potential to perform better if drilled with something other than conventional drilling methods and in some cases better than a typical fracturing application.
  - Increased reserves as a result of "uncovering" zones that previously would not produce as a result of conventional drilling induced damage effects.
- Real-Time Reservoir Evaluation (RTRE™):
  - As an option for added value to the underbalanced operation, Halliburton offers real-time well testing while drilling for reservoir characterization. This can provide invaluable data for asset optimization, stimulation design, and other production optimization processes. The RTRE service greatly increases the probability for the "high reward" of the underbalanced operation.

Management analysis of the cost versus the benefits of using underbalanced technology must determine not only that the payoff potential is great but also that the personnel providing the underbalanced service have a successful track record using and managing their equipment and technology.

The objective in drilling underbalanced is to allow the reservoir to flow through the productive interval while drilling. This is achieved by drilling with a pressure that is lower than the formation pore pressure. Outward pressure from the flowing reservoir prevents the formation from receiving fluids. Drilling fluid will not be lost in large quantities and the drill pipe will not be differentially stuck.

In contrast, conventional overbalanced drilling utilizes a drilling fluid pressure that is greater than the formation pore pressure. Because of the overbalanced condition, drilling fluid filtrate is invariably lost to the reservoir[12]. Loss of drilling fluids may potentially damage the reservoir in both the near wellbore and far field, thereby resulting in high "skin" values which can reduce the ability of the well to produce. The far field damage is of serious concern as this may pre-empt any success with conventional stimulation to recover the wells produce-ability.

Underbalanced drilling is an effective means for optimizing production. Production rate increases of ten or more times over projection are not uncommon. Underbalanced drilling fluid, which sometimes includes compressed gas, is injected into the wellbore to lighten the hydrostatic column. Underbalanced drilling fluid typically travels down the drillstring and exits through the bit.

The formation exposed by the bit experiences a lower pressure in the wellbore than the pressure in the formation. The physics of a bit drilling a rock layer is enhanced by this pressure loss. Conversely, the conventional method has the drilling fluid pressing into the rock layer while the bit attempts to cut it.

Because the bit encounters less pressure than it would with overbalanced drilling, it will grind through rock at a greater rate than normal, thus increasing rate of penetration. While production optimization is a key driver in choosing underbalanced applications, other drivers relate to reducing operating expenditures by minimization of expensive mud losses and eliminating the inefficiencies and lost time due to differential sticking.

In conventional well construction, the norm is to allow formation flow, or influx, only after well completion. On the other hand, underbalanced drilling allows formation flow during the drilling process. Spindle Top is the classic example of an underbalanced well, but in an uncontrolled, dangerous manner.

Tremendous advancements have been made since then in understanding pressure and its effects. If done correctly, the additional planning and control exhibited by a typical underbalanced project can actually result in a safer working environment. What this means, though, is that to drill an underbalanced well correctly, the fluctuating pressures, flow rates, and temperatures must be constantly and accurately monitored in order to achieve a safe condition during the entire cycle, from the point of injection; while drilling; and as the cuttings, drill fluid, water, oil, and gas reach surface.

While pressure, flow rate, and temperature sensors are monitored manually, additional reliability is gained when the data is acquired by a computerized system. This Data Acquisition System (DAS) acquires surface data as well as all other rig sensors and downhole sensors, through the use of a common protocol called WITS (wellsite information transfer specification)[13].

Chapter 17 :

OMAN FIELD TEST COMPARISON OF UBD AND OBD

17. OMAN FIELD TEST COMPARISON OF UBD AND OBD

In Oman's Saih Rawl oil field, the underbalanced drilling technique was successfully field-tested, achieving the goal of minimizing formation damage while markedly improving the productivity index.

Utilization of underbalanced drilling (UBD) at Petroleum Development Oman (PDO) stretches back to sporadic projects in the mid-1990s. However, not until recently were tangible gains realized using this technique. Although UBD's benefits are widely accepted within North America, the technology has not been fully exploited internationally for several reasons, particularly justification of increased drilling costs against perceived "intangible" benefits. Such justification is particularly hard for asset managers and well planners to make in the absence of concrete industry data on production increases[14].

PDO embarked on a focused campaign to trial UBD and evaluate its applicability as an enabling technology. 1 A "zero cost implementation" approach introduced the campaign, and drilling began in June 2002. Oil wells targeted in Saih Rawl field are underpressured, drilled as five-legged producer-injector pairs off a 7-in. backbone. The wells are normally completed with ESPs[14]. Engineering for the Saih Rawl UBD project focused on the asset team's mandate to eliminate reservoir damage. Equipment was chosen accordingly, and a program was developed to inject field gas via a concentric casing string to establish UBD conditions.

Because the technology was newly re-introduced to PDO and its local contractors, a step-by-step approach was adopted for the first well, and it ultimately demonstrated UBD's benefits. Post-drilling flow tests proved invaluable for evaluating UBD's applicability - results showed distinctly increased production from adjacent legs about 200 m (762 ft) apart in the same reservoir[15]. Various design issues were solved, and results of drilling the SR 153 well were deemed successful.

Chapter 18:

REAL TIME RESERVOIR EVALUATION OF UBD AND OBD

18. REAL TIME RESERVOIR EVALUATION OF UBD AND OBD EVENT

The Halliburton underbalanced applications (UBA)– real-time reservoir evaluation (RTRE) is a comprehensive engineering process that integrates and sequences surface and subsurface data obtained during underbalanced drilling.

This data is evaluated to characterize the reservoir and yield valuable production data such as productivity index and permeability[16]. The process begins with preliminary analysis of offset well data and design of testing procedures to maximize the reservoir information obtained during the drilling process.

The Halliburton INSITE® system of data acquisition and data management brings the data to one platform after which a unique reservoir model is used to analyze the pressure and rate data to determine reservoir productivity.

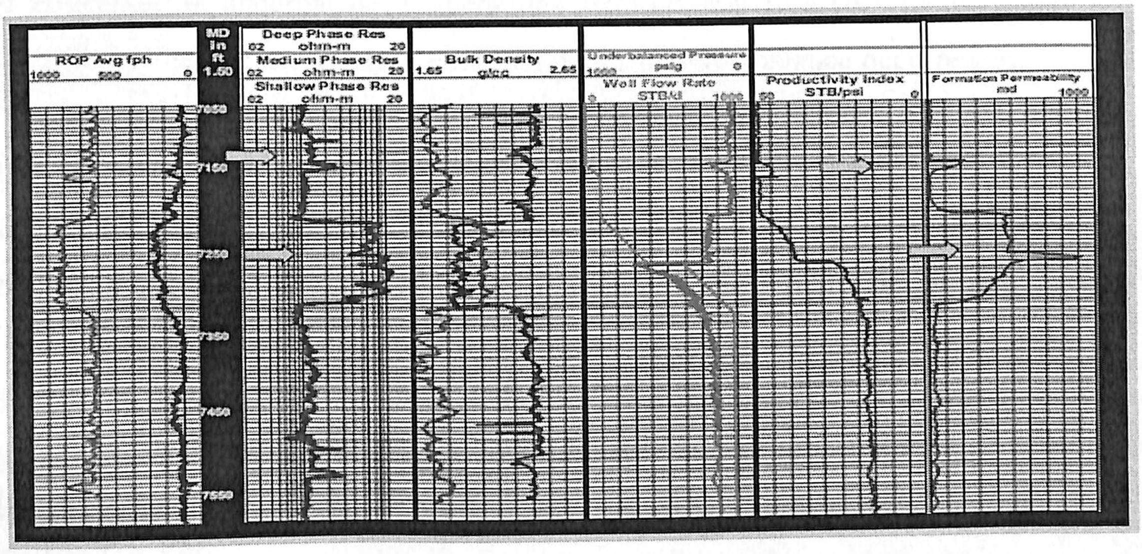
One of the components of this reservoir model, TimeSplice, is initially used to transpose and correct the surface rate data to the bottomhole, taking into account the injection and production lag times. The bottomhole pressure corresponding to each traversed layer in conjunction with other input data is then used by the analytical transient reservoir model to calculate the rate from each productive zone[16]. To characterize the reservoir even more accurately, the numerical reservoir simulator component can be used.

Reservoir engineers and geologists work together to interpret the results from the predictions and advise the on-site engineers of any additional testing required for further reservoir characterization or modifications to drilling plans.

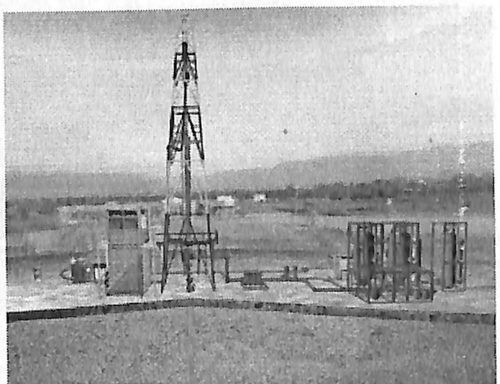
This "testing while drilling" methodology yields important reservoir information that in many cases greatly changes the reservoir knowledge in a field. Reservoirs which previously did not merit testing are automatically tested during the drilling phase providing reservoir knowledge to the asset manager.

The Halliburton RTRE is composed of tools that allow this data to be analyzed accurately and rapidly by amalgamating several advanced techniques and methodologies. There have been cases where zones previously not "seen" or not deemed productive with conventional drilling were found to contain economic reserves to justify completion.

Figure 1 illustrates where previously deemed non-commercial pays (indicated by the top yellow arrows) make significant contributions to total production rates when not exposed to the damage of overbalanced drilling. The reservoir evaluation capability of Halliburton UBA maximizes the discrete characterization of these intervals allowing for full exploitation of the reservoir.



The first approach was to synchronize the surface measured injection and production rates to bottomhole, so that a representative sandface rate for each layer could be determined.



Secondly, the nature of reservoir pressure transient testing had to be modified to account for the dynamics of having an ever changing reservoir height as the bit progresses through the pay.

This meant that a moving boundary condition problem had to be solved. Once this solution was implemented, it was verified against more conventional industry pressure transient analysis models (for the simplest case of a constant wellbore length) and against numerical simulators (for increasing well length), giving results within a 5% tolerance.

The broader implications of this approach may mean better reservoir characterization in less time than the industry standard wireline-based evaluation, especially when coupled with some basic logging while drilling tools[16].

For the asset manager, even more valuable information can be gained about the reservoir. In many conventional underbalanced operations without this reservoir focus, a pay interval is drilled mostly underbalanced but often with some overbalance occurrences.

The result of this temporary overbalance is often overlooked and never quantified. Using the RTRE with its detailed data acquisition and analysis ability, many overbalanced events are now quantifiable, leading to very accurate information on the cost of failing to achieve true continuous underbalanced drilling. Figure 2 is a simulation extracted from a composite of field cases which were seen with the UBA-RTRE. As pay is intersected in an underbalanced environment, the RTRE kicks in, resulting in an accurate quantified reservoir characterization.

As sometimes happens, an unplanned pressure event throws the system into overbalance, even for relatively short period of time. After Underbalanced conditions are returned, the damage to the reservoir can be expertly determined.

In Damage Rate 1, a five-fold reduction in rate is determined. After an extensive effort to "blow out the damage" with greater drawdown pressures, the Damage Rate 2 is seen to be 2.5 fold. The most significant observation is that for this case, the damaged formation never cleans up to original rates over the observed period.

The information from this qualified result is modeled by the RTRE and the resulting loss of productivity is quantified to an accurate value, giving the operator an exact evaluation of the lost production due to overbalance. In the typical well seen by Halliburton UBA, the loss of production over the life of the well greatly exceeds the cost of implementing the RTRE in conjunction with sound project management and engineering processes required to prevent these unplanned overpressure events.

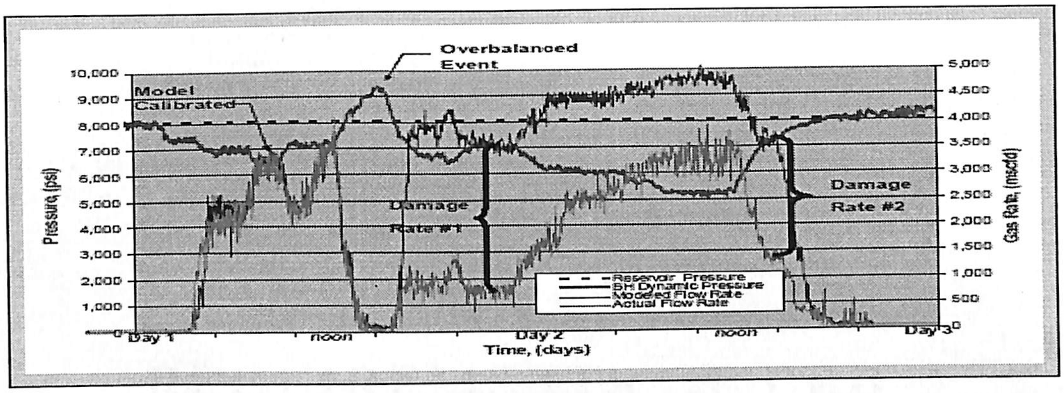


Figure 2: Simulated Underbalanced Job Chart with Overbalanced Event (composite of field cases)

Chapter 19 :
REQUIREMENTS OF UBD TECHNOLOGY

19. REQUIREMENTS OF THE UBD TECHNOLOGY

Experience has proven that planning, implementing and sustaining a quality UBD project requires effective management and provision of a skillful team through each phase of the project. FX's UBD Project Management template provides an excellent starting point for the UBD project manager to plan and implement the UBD project and project resources.

The template contains a concise list of (document) deliverables that he will be required to manage and aids to developing the UBD Project Plan. All disciplines and activities are featured including Reservoir Engineering, UBD Engineering, Drilling, Production Engineering and special attention is given to the management of HSE in UBD.

Not only should the project manager deliver an on-time and on-budget project but he should also ensure to leave a well document legacy of the project, which includes everything from the Concept Selection (Basis of Design), the Detailed Design (P&IDs etc.), the Implementation (well reports etc.) and culminating in the evaluation of results.

Good HSE management that addresses all aspects of HS&E is a fundamental part of UBD planning and operations and will be addressed in the detailed engineering phase. Current HSE data-trends indicate that HSE is being managed effectively in underbalanced drilling operations and compare very favorably with conventional drilling operations.

Historically a **minimum** of six (6) months is required to satisfy all of the phases required to properly plan and execute a successful UBD campaign[17]. If the timeline is tight, many of the project phases must be conducted in parallel, specifically to the tender exercise. For example, if the detailed engineering phase does not commence until the "official" award of services, the project will not likely meet the deadline. It is strongly suggested that a project manager is employed as soon as the UBD concept is approved to begin tender preparations. This role can either be satisfied by a qualified personal internal to the Client or FX can provide a dedicated resource.

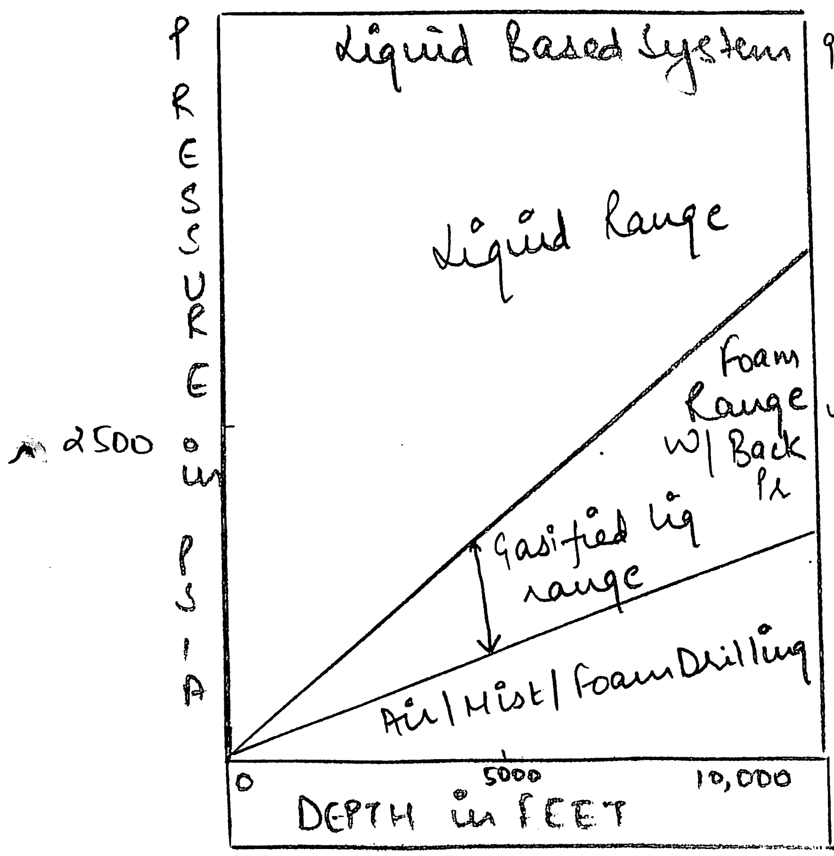
Chapter 21 :

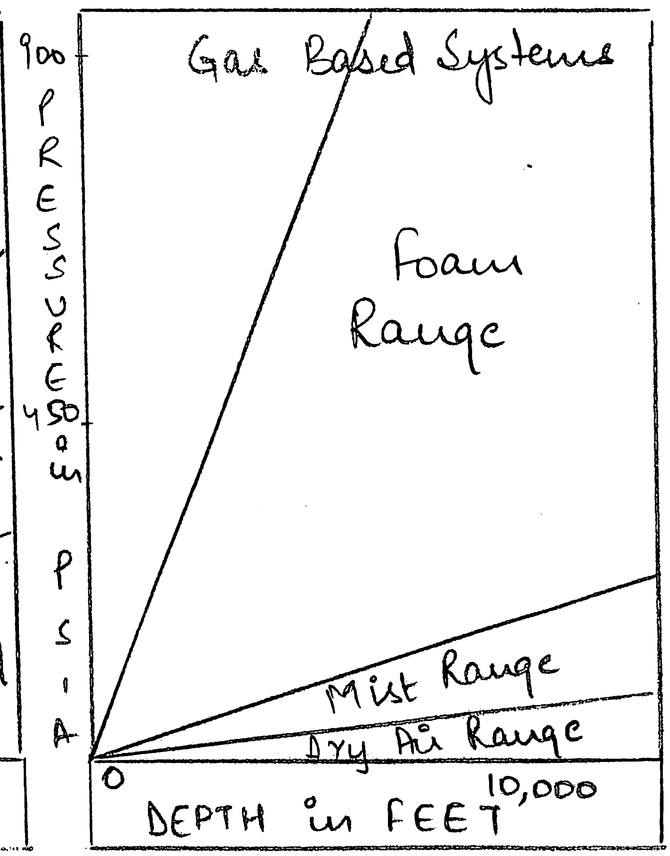
TECHNICAL ASPECT OF UBD

21. TECHNICAL ASPECTS

a. Well bore Stability

The first decision to start quantifying the economics of drilling Underbalanced is to determine if the pressure restraints on the wellbore dictate a gas or liquid system, or fully excludes UBD. Once the pressure limits have been determined, the system type can be determined using the charts below, figure. Once the system is chosen, estimates can be prepared on daily costs since it further defines what equipment will be necessary[17].





b. Defining the Pressure Limits

To define the pressure limits, a sonic log or Underbalanced drilling information from an offset is needed. The upper limit, by definition, is the pore pressure plot. The lower limit must maintain wellbore stability. It is possible to calculate pressure differentials from the sonic log. This requires both the compressional wave velocity and the shear wave velocity which may not be available. As a thumb rule, a well with sonic travel times consistently below 70 ms is probably a good air drilling candidate. If offset information exists, the lowest pressures without wellbore problems can be used with the above charts to determine which system can be applied. At this point in the design, the decision to use a gas or liquid based system is enough to continue. Later in the design, other information will be added to determine precisely which system and what additives will be required.

c. Increased ROP

Will the well drill faster Underbalanced??

The increased ROP associated with Underbalanced drilling must be discussed as two different subjects. The division is permeability. In permeable rock the mechanics of increased penetration are different from the increased ROP in impermeable rock.

d. Permeable Rock

The increased penetration rate due to drilling Underbalanced is related to permeability and differential pressure. The hold down forces on a cutting, combined with the time required for the pressure at the cutting to equalize appears to be one of the driving forces of ROP in permeable rock. In a tight formation the time is significant for the differential pressure holding the cutting in place to equalize and release the cutting. The differential is critical to ROP. With high permeability the time is shorter. The most gains in ROP experienced in a permeable formation will be in an under pressured zone where the typical overbalance is high. The greatest gains in ROP seen in a permeable zone are in the overbalanced to balanced range. This will increase typically ROP by 30% to 300% depending on the initial overbalance. In cases where the formation is underpressured, the overbalance is very high and the gain can be 1000%. From balanced to Underbalanced is usually a small gain, 10%-

20%, compared to OB to balanced. Keep in mind that in many cases reaching the balance point requires some form of "Underbalanced drilling".

e. Impermeable Rock

In impermeable rock, the mechanics of increased ROP appear to be absolute BHP. The inability of the rock to equalize allows all of the potential energy stored in the formation that is pressure, to appear as drilling energy. The lower the borehole pressures the faster the ROP. This explains, in part, the increased bit life experienced in UB drilling. The bit does less work so it drills more feet before it is worn out.

f. Summary

Rules of thumb are convenient for estimating ROP for a macroeconomic look at the well. A good, safe method of projecting ROP when better information does not exist is to either double the ROP below 50'/hr or add 50% above 50'/hr. There is no basis for this rule. Through reading the literature and case histories the increase is 0% to 1000% but 100% increase appears to be a safe low end for most cases where the original ROP is not extremely high.

Chapter 22 :

MACRO-ECONOMICS

22. MACRO-ECONOMICS

Determine if there is a benefit that may translate to dollars to economically justify the well.

The picture on economics involves three different comparisons.

- The daily cost for the projected number of days for each method plus the cost
- for construction, mobilization, disposal, and reclamation, gives a good first look at the comparative direct costs.
- The benefit of increased production and additional produceable reserves, or the savings from not stimulating the well provide the second bit of information.
- The risk cost for lost circulation, environmental damage, safety concerns, lost BHA, sidetracks, etc. can be factored in to complete the economic overview.

Some items are difficult to quantify. On the other hand, simple economics can be used. For example, if 25% of the wells in a field have required a $ 500,000 sidetrack, the risk cost is $ 125,000. If Underbalanced drilling can cut the number of sidetracks in half, a reduced risk cost of $ 62,500 can be assigned to the well. When the risk cost is added to the well cost, a more realistic picture is presented[18].

Time Requirements

Will the overall drilling time be shorter?

The following are two simple examples to show how ROP can be used as a quick look for economics.

Case: A well has a 3000' section drilled with mud with 100 connections at 5 minutes per connection. This equates to 8.3 hours for connection time. It takes 3 hours to trip in to 6000' and 4.5 hours to trip out from 9,000'. The total trip time with mud is 7.5 hours.

Example 1: Hard Section:

Air vs. Mud: Double penetration rate (5' mud, 10' air) plus 50% longer on connections and trips:

Fluid	Rot. Time	Conn. Time	Trip Time	Total Time
Mud	600 hr	8.3 hr	7.5 hr	615.8 hr
Air	300 hr	12.5 hr	11.2 hr	323.7 hr

Example 2: Softer more permeable section:

Gasified liquid vs. Mud: Add 50% to penetration rate (150' gas/liquid, 100' mud) plus 100% longer on connections and trips:

Fluid	Rot Time	Conn. Time	Trip Time	Total Time
Mud	30 hr	8.3 hr	7.5 hr	45.8 hr
Gas/Liq	20 hr	16.6 hr	15 hr	51.6 hr

It becomes obvious that ROP is only a major concern if significant time is spent rotating.

Increased Production

- Decide if the well will produce more if it is drilled Underbalanced.

There may be a definable increase in production with two effects: the NPV of the production increases and the economic limit of the production may be extended. These two benefits, increased early production and increased reserves may combine to justify additional expenditure for Underbalanced drilling.

Using standard calculations for PI in a vertical well, the comparison for a skin of 5 and 0 is shown in the following example.

Example: Offset wells have been shown to have a drilling induced skin of 5. The PI calculation is as follows:

k= 100 md, h= 50', μ= 2 cp, Bo= 1, Re= 2106' (320 Ac), Rw= 0.354' (8.5"),

$$M = \frac{0.00708kh}{\mu Bo\,[\ln Re/Rw - 0.5 + s]} = \frac{35.4}{16.38+2s}$$

With a skin of 5, drilled overbalanced, the production rate with 500 psi drawdown will be 670 BOPD. With a skin reduced to 0 by drilling Underbalanced the rate will be 1080 BOPD. The increase of 410 BOPD at a net of $ 15/Bbl is an additional $6,150 per day. The first month nets an additional of $184,500. This is enough to cover the extra drilling expense.

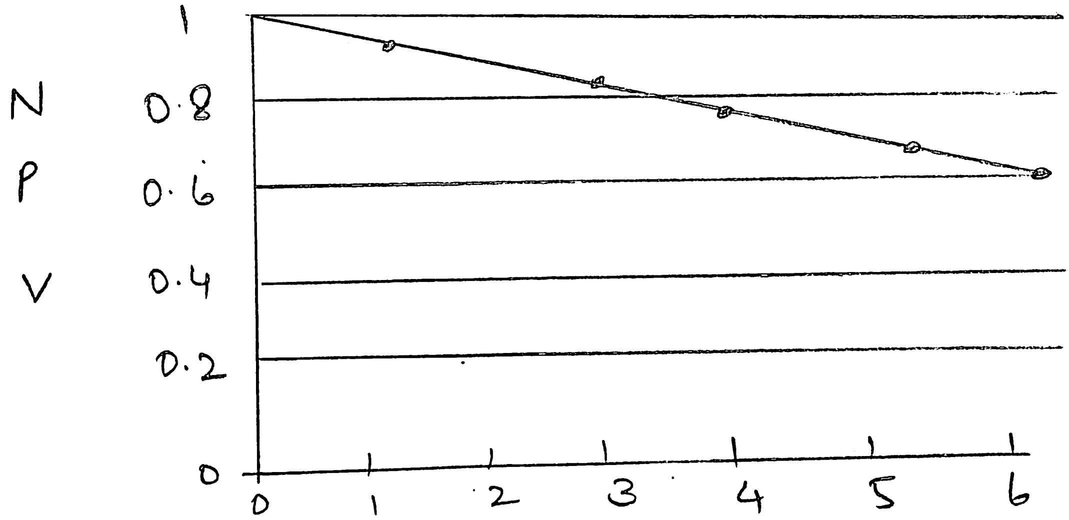
In the same example: The initial production is 670 BOPD and 1080 BOPD respectively. Using decline rates of 5% and 8%, which is the same ratio as the production ratio, and an economic limit of 50 BOPD then:

The damaged well produces 380,000 Bbl oil in 52 months and is then shut in.

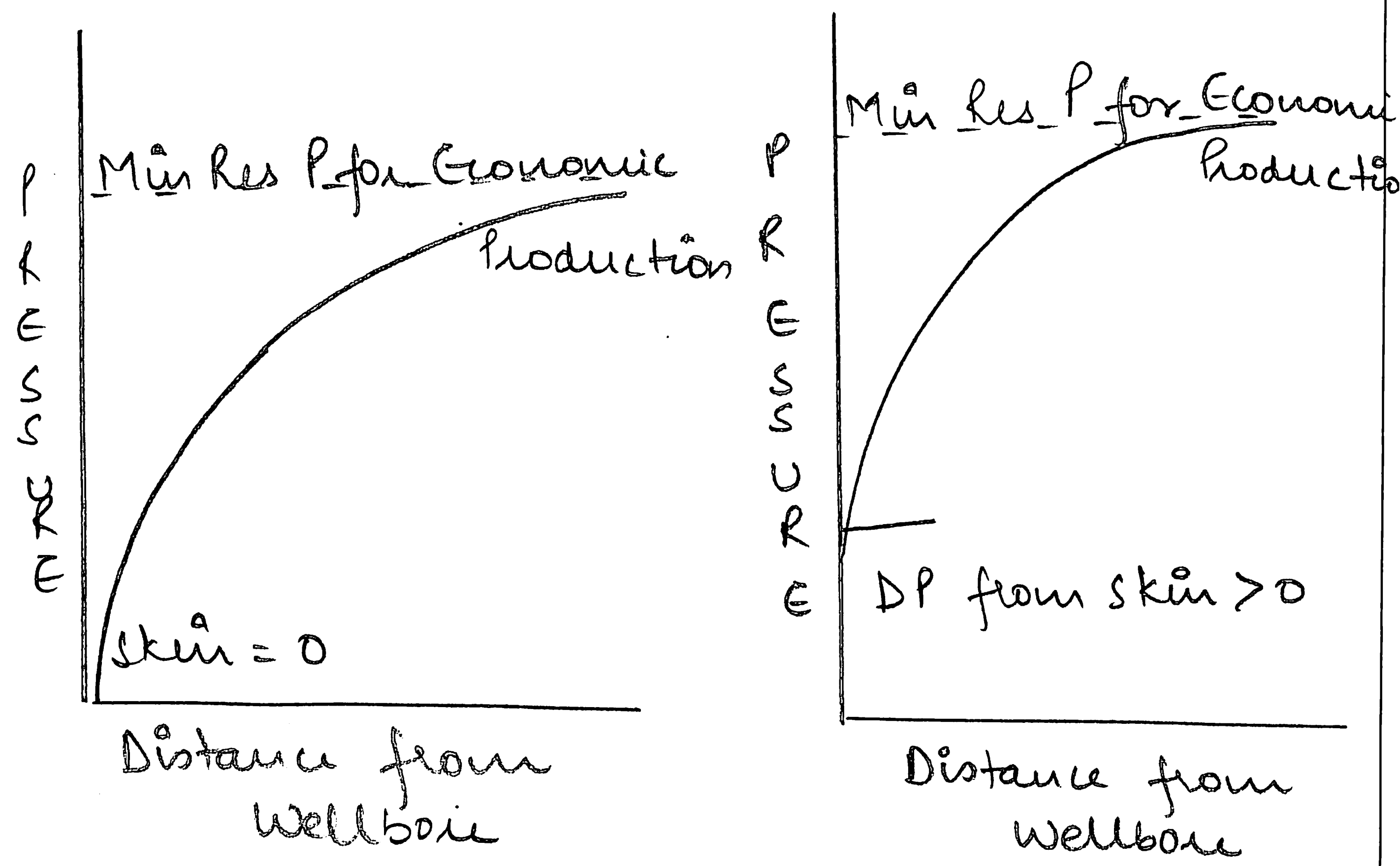
The undamaged well produces 394,000 Bbl oil in 38 months.

The increase in net present value (NPV) is a combination of faster production and increased production. The calculations of the net present value for these two examples are based on a 10% investment opportunity rate[18]. The following chart is NPV as a fraction based on 10% discount rate,

$$\mathbf{NPV = \Sigma\,(1+Dr)^{-t}}$$



The increased production is based on a lower abandonment pressure before the well reaches its economic production limit. The following figure is an example of the difference in abandonment pressures.



YEAR	NET PRICE	PROD S=5	VALUE	PROD S=0	VALUE
1.	$15.00	187,697	$ 2,815,455	260,104	$ 3,901,560
2.	$ 13.63	101,321	$ 1,381,005	95,556	$ 1,302,435
3.	$ 12.39	54,717	$ 677,943	35,075	$ 434,579
4.	$ 11.26	29,646	$ 333,813	3,141	$ 35,367
4-1/2	$ 10.80	6,435	$ 69,508	0	0
TOTAL		$ 379, 816	$ 5,277,724	393,877	$ 5,673,941

The increased oil recovery is 3.6%, and the increase in NPV is 7.5% or $ 396,217.

Chapter 23 :

COST ESTIMATION

23. COST ESTIMATION

All cost estimates should be broken out by whether they are general or specific to drilling Underbalanced. It will be necessary to write and AFE for OB and for UB and compiling costs with that in mind will make the comparison much easier.

C. Elements

a) Tangible Costs

Unless there is parasitic injection, or a casing string is eliminated or added, this will be the same for UB as OB.

b) Construction

After location and pit requirements are set call a location contractor. Have them bid the standard location plus the UB drilling location if there are differences[19].

c) Mobilization

Include rig, pump system, returns system

d) Daily Costs

Determine daily costs. Include rig, all rentals, extra personnel, monitoring equipment RBOP, etc. Any charges that will continue throughout the well should be included. Separate the costs into UB drilling costs and general well costs.

e) Pumping System

Any additional costs above mobilization and daily rental cost such as estimated repair costs.

f) Additional BOP

Any one time charges on the RBOP above daily rental like repairs or reconditioning at the end of the well.

g) Return System

Additional costs on the return system not covered by the daily rental similar to the BOP.

h) Additional Costs

Include any costs that are time specific like directional costs or additional equipment[20].

Item	Estimated Cost
LOCATION EQUIPMENT	
Compressor System Air/Mist	**$ 1450/day plu $ 32/hr/fuel**
Compressor System Foam	**$ 1125/day plus $ 22/hr/fuel**
Compressor System Gasified Liq.	**$ 1050/day plus $ 16/hr/fuel**
Cryogenic Nitrogen N2/Mist/Foam/GL	**$ 1.95/100 ft3 + $ 2615/day/pump+ $ 1500/day/trk**
Membrane Nitrogen N2/Mist/ Foam/GL	**$ 3000/day + $ 1700/day/diesel**

Natural Gas Supply Gas/Mist/ GL	**$ 2.00/MCF**
Booster Gas/Mist/GL	**$ 350/day + $ 16/hr/fuel**
Valve Manifold-Filter Gas/Mist/GL	**$ 65/day**
Skimmer Tank System GL/FD	**$ 1350/day**
Super Gas Buster GL/FD	**$ 210/day**
Blooey Line Air/N2/Gas/Mist/Foam	**$ 75/day**
Gas Sniffer Air/N2/Mist/GL	**$ 20/day**
Pilot Light Air/N2/Mist/GL	**$ 20/day**
Closed System Separator Flow Drilling	**$ 3910/day**
Fluid Storage Flow Drilling	**$ 80/day**
N2 Unit Standby Flow Drilling	**$ 765/day**
Fluid Pump GL/FD	**$ 2750/day**
Choke Manifold Sysem GL/FD	**$ 250/day**
DOWNHOLE EQUIPMENT	
Fire Float- Fire Stop Air	**$ 345/10 day min + $ 26/day/each**
Drill String Floats A/N2/G/M/F/GL	**$ 500/each**
Rotating Control Head A/N2/G/M/F/GL	**$ 110/day + $ 515/elements/each**

Rotating BOP FD/MD	**$ 1000/day + $ 1200/elements/each**
Snubbing Unit Snub Drilling	**$ 7075/day**
Air Insert Bits A/N2/G/M/F	**6 ¼" $ 3770- 7 7/8" $ 4175- 8 ¾" $ 4695**
Air Hammer Insert Bits A/N2/G/M	**6 ¼" $ 3685- 7 7/8" $ 5621- 8 ¾" $ 6667**
Air Hammer A/N2/G/M	**$ 72/hr**
MM-MWD-GR Flow Drilling	**$ 6500/day**
MM-MWD-GR C.T.GL/FD	**$ 8850/day**
Mud Motor A/N2/G/M/F/GL/FD	**$ 165/day + $ 150/day/monel & kit box**
Chemicals	
Liquid & Solid Additives Mist Drilling	**$ 2500/day**
Liquid & Solid Additives Stable Foam	**$ 4000/day**
Liquid & Solid Additives Stiff Foam	**$ 3500/day**
Corrosion Inhibitor M/F/GL	**$ 300/day**

Chapter 24 :

CASE STUDY FOR TECHNICAL AND ECONOMIC FEASIBILITY ANALYSIS

24. CASE STUDY FOR TECHNICAL AND ECONOMIC FEASIBILITY ANALYSIS

A. CANDIDATE SELECTION

The UBD candidate for this exercise was chosen as a fairly typical multiple gas zones, fractured reservoir. The offset comparison well, the Typical #1, is a 6000' vertical well drilled on 160 acre spacing. The target reservoir is a gas bearing sandstone with 30 milidarcy permeability and 40' of net pay in two intervals. The intervals are 5200'-5220', and 5800'-5820'. It is common to lose partial returns in the pay section area when drilled overbalanced due to the natural fracturing. The initial production rate from the two zones is approximately 278 mcfd and theskin factor has been determined to be +10. Due to the proximity of water, fracture stimulating the zone is not feasible. The purpose of the exercise is to evaluate the economic feasibility of drilling the offset well Underbalanced. The only change in reservoir parameters as a result of the Underbalanced drilling operations will be the reduction of the skin to zero[21].

B. ANALYSIS OF THE CANDIDATE

❖ ***OFFSET DATA GATHERING ANDANALYSIS***

a) Offset Data Gathering

1) Upper Hole Section (Surface shoe to 5150')

a) Hole Section Properties

- Pore Pressure Plot for the interval - Normal
- Pressure Variations - No charged/ Depleted Zones
- Presence of Lost Circulation Zones- No Lost Circulation Zones

- Location of Water Zones - Water Zones from 2200' to 2420'
- Productivity of Water Zones - High Productivity Brackish Water Zones
- Time vs. Depth Plot - 8 Days to Mud Drill Section (7 7/8" hole)

b) Rock Properties

- Formation Strength - Low Strength Water Zones (Minimum Allowable gradient 0.43 psi/ft)
- Water Sensitive shales section - No water sensitive shale zones
- Erosion Potentials - High Erosion potential of water zones

c) Influx Fluid/Drilling Fluid Compatibility

- Emulsion Potential - Low
- Scale Potential - Low
- Corrosion Potential - High
- Contamination of Circulating fluid by Influx - High

d) Rock/Drilling Fluid Compatibility

- Potential Reaction with clays and shales - Low
- Formation Dissolution - Low
- Reactivity and Transport of Cuttings - Low

2) Production Hole Section (5150' to 6000' TD)

a) Reservoir Properties

- Current Target reservoir pressure - (0.338 psi/ft) (BHT 123 deg F)
- Presence and pressure of multiple zones- 5200'-5220' & 5800'-5820'

- Pressure variation within the reservoir – None
- Location of Oil, Gas, and Water Contacts – Gas Column only
- Presence of Sealing/Non-sealing faults- None

b) Rock Properties

- Reservoir Lithology - Limestone
- Vertical and Horizontal Permeability - 30 md
- Porosity - 14%
- Pore size and pore throat distribution - N/A
- Presence of faults, fractures, vugs etc - Highly fractured
- Formation Strengths - Fracture Gradient 0.90 psi/ft
- Initial Saturation - Sw <60%
- Capillary Pressure Characteristics - N/A
- Wetability - N/A
- Relative Permeabilities - N/A
- Glazing Potential - N/A

c) Reservoir Fluid Properties

- Compositions - 0.02 bbls condensate/mcf gas
- Asphaltine/Paraffin Contents - N/A
- Cloud and Pour Points - N/A
- Viscosities and Densities - Gas Gravity 0.84
- Bubble point and PVT properties - N/A
- Dew point and CVD properties of Rich gases - N/A
- Presence of H_2S/other hazardous material - None

d) Reservoir Fluid/Drilling Fluid Compatibility

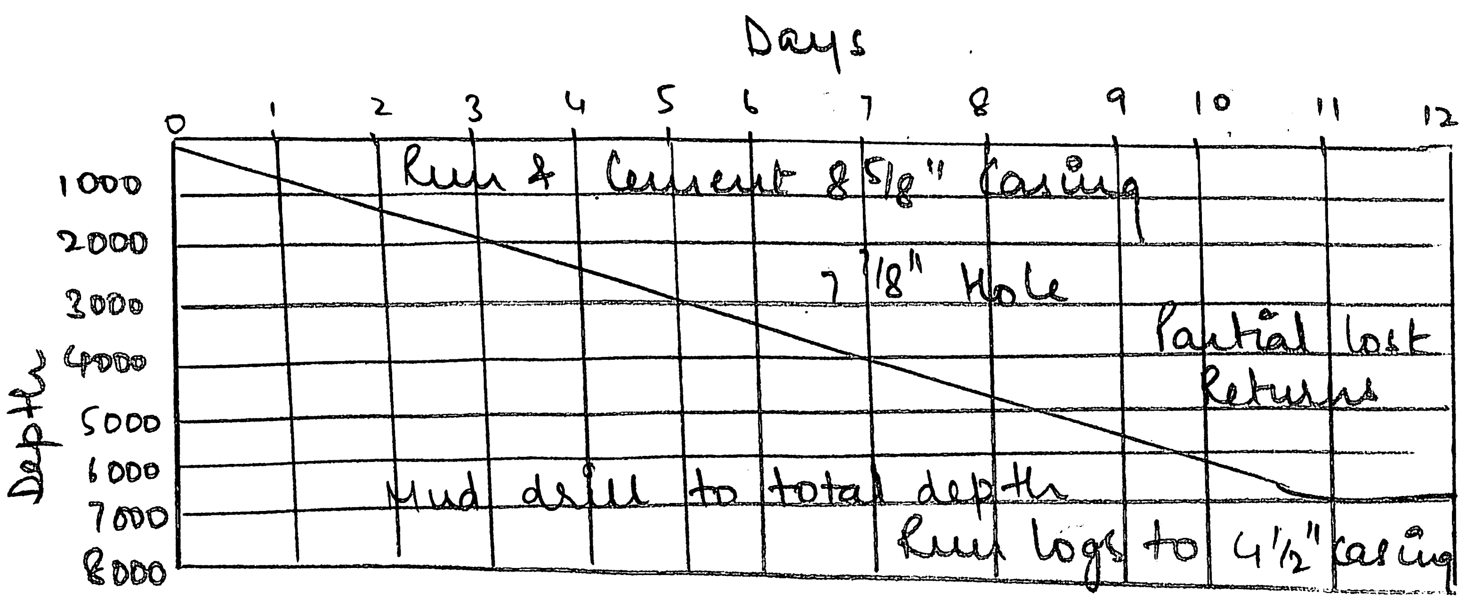
- Emulsion Potential - Low
- Hydrate Potential - None
- Precip. Or Asphalt Deposition Potential - None
- Gas Entrainment Characteristics - Normal
- Explosion Potential - High
- Corrosion Potential - Low
- Degradation of Drilling Fluid by formation fluids - Low

e) Reservoir/ Drilling Fluid Compatibility

- Potential Reaction with clays - Low
- Potential reaction with hydratable shales - Low
- Formation Dissolution - Low
- Countercurrent imbibition Potential - High- skin factor of 10
- Reactivity and transport of cuttings - Low

b) Typical # 1 well data analysis

1) Typical # 1 Drilling Time vs. Depth Plot



2) **Typical # 1 Flow Rate (Zone 5200'-5220')**

Lease Name **Typical # 1**
State, County
Field Name

Pwf	757	Psia
BHP	1,757	psia
Drainage area	160	Acre
Well Bore radius	0.328	Foot
Net thickness	20	Foot
N factor	0.7000	
Reservoir Temp.	123	F
Permeability	30	Md
Skin factor	10.00	
Gas Gravity	0.840	
%N2	0.00	%
%CO2	0.00	%
%H2S	0.00	%
Condensate (yes)	1	
Res Temp.	584	R
Re	1,490	Ft
Viscosity gas	0.0129	Cp
Wconst	0.5007	
Pseudo	Y	(Y or N)
Z factor gas rate	0.731 135	Mcfd

3) **Typical # 1 Flow Rate (Zone 5800'-5820')**

Lease Name **Typical # 1**
State, County
Field Name

Pwf	960	Psia
BHP	1,960	psia
Drainage area	160	Acre
Well Bore radius	0.328	Foot
Net thickness	20	Foot
N factor	0.7000	
Reservoir Temp.	123	F
Permeability	30	md
Skin factor	10.00	
Gas Gravity	0.840	
%N2	0.00	%
%CO2	0.00	%
%H2S	0.00	%
Condensate (yes)	1	
Res Temp.	584	R
Re	1,490	Ft
Viscosity gas	0.0136	Cp
Wconst	0.5007	
Pseudo	Y	(Y or N)
Z factor gas rate	0.722 143	Mcfd

4) **Typical # 1 Economic Analysis (Both Zones)**

Well Name **Typical # 1**
Prospect

Gas Price	$ 1.50	($/gas unit)
Oil Price	$ 18.00	($/oil unit)
Working Int	1.00000	(fraction)
Revenue Int.	0.80000	(fraction)
---Gross—First		
Reserves	550,000	(gas unit)
Initial Rate	278	(unit/day)
Yield	0.02	(BO/Mcfg)
Prod. Tax rate	0.0700	(fraction)
Lease and	$ 0	
Drilling costs	$ 149,500	
Completion	$ 141,000	
Operating costs	$ 1,235	($/MO)
Drilling promot	1.00	
Time till drilled	0.00	YR
FNR	$ 130,635	
PW (10)	$ 27,138	
PW (20)	($ 34,412)	
PW (30)	($ 73,708)	
PW (40)	($ 100,153)	
PW (50)	($ 118,669)	
PW (60)	($ 132,023)	
Total Costs	*$290,600*	
First Year	$ 89, 838	Rev
Two Years	$ 164,179	Rev
Five Years	$ 315,521	Rev
Payout	4.38	Yrs
ROR	13.94%	
ROI	1.45	

2. Underbalanced Design

a) Which systems apply (Compatibility of hole section to drill Underbalanced)

1) Upper Hole Section

- Presence of High productivity brackish water zones
- Presence of low formation strength zone
- Presence of high erosion potential zones
- High corrosion potential from influx fluid
- High contamination of drill fluid from influx
- 8 days to mud drill section

2) Production Hole Section

- Low target reservoir pressure (0.338 psi/ft)
- Presence of fractures (partial lost circulation)
- No hazardous components (H_2S)
- High explosion potential
- Low potential reaction with clays and hydratable shales
- High countercurrent imbibition potential (skin factor of 10)

b) Pick the system

1) Upper Hole Section

- Mud Drill Overbalanced

<u>Reason: High capacity brackish water influx- disposal is unfeasible</u>

2) Production Hole Section

- N2 Fluid Drill Underbalanced

Reason: Minimize gas handling during drilling

c) Underbalanced Data Analysis

3) Fluid Design

a) Fluid Weight

- 8.4 PPG 2% KCL Base fluid
- N2 injection
- 0.322 psi/ft ECG

b) Corrosion Program

- None Required

c) Circulating Rates

- 160 GPM 2% KCL fluid
- 700 scfm N2 injection
- 100 psi Back Pressure
- 115 fpm minimum cutting velocity

d) Fluid Recipe

- 2% KCL Fluid

e) Material Requirements

- 600 BBLS 2% KCL Fluid

4) Disposal Volumes

a) From fluid system

- 600 BBLS 2% KCL Fluid

b) From Well Influx

- Influx gas and condensate to be flared
- No influx of formation water

C. EQUIPMENT SPECIFICATION

Addition equipment required to drill Underbalanced

- Rotating head
- Gas buster
- Drill string fluid
- Portable N2 membrane system (1500 scfm at 5000 psi)

D. COST ESTIMATION

DRILL AND COMPLETE- OVERBALANCED MUD DRILLED

Intangible Cost	Dry Hole 12- Days	Completion 7-Days	Total Cost
Location- survey and permit	$ 400.00		$ 400.00
Location-road/maint.	$ 7,000.00		$ 7,000.00
Location- damages	$ 2,000.00		$ 2,000.00
Reclamation/P&A		$ 3,100.00	$ 3,100.00
Drilling rig- rig move	$ 6,500.00		$ 6,500.00
Drilling rig-contract	$ 54,000.00		$ 54,000.00
Drilling rig-turnkey			
Drill bits/stabilizers	$ 17,300.00	$ 1,200.00	$ 18,500.00
Mud & chemicals	$ 13,000.00	$ 600.00	$ 13,600.00
Mud equipment			
Water-purchase/hauling	$ 10,000.00	$ 400.00	$ 10,400.00
Logging-mud			
Logging-open hole	$ 8,800.00		$ 8,800.00
Logging- cased hole		$ 1,500.00	$ 1,500.00
Coring & analysis			
Testing & analysis			
Cementing-surface	$ 4,100.00		$ 4,100.00
Cementing-intermediate			
Cementing-production		$ 12,000.00	$ 12,000.00
Cementing-squeeze			
Rental-completion tools		$ 2,500.00	$ 2,500.00
Rental-other			
Completion rig		$ 10,500.00	$ 10,500.00
Perforating		$ 3,000.00	$ 3,000.00
Acidizing		$ 5,000.00	$ 5,000.00
Hauling/trucking	$ 1,000.00	$ 1,000.00	$ 2,000.00

Contract labor	$ 6,000.00	$ 8,000.00	$ 14,000.00
Prof. serv-geologist	$ 1,000.00		$ 1,000.00
Prof serv- engineer	$ 6,500.00	$ 4,000.00	$ 10,500.00
Prof. serv- drig. Foreman			
Prof serv.-other	$ 200.00	$ 700.00	$ 900.00
Admin. Fees-other	$ 2,700.00	$ 2,700.00	$ 5,400.00
Broker fees			
Misc. expenses	$ 1,500.00	$ 1,500.00	$ 3,000.00
Contingencies	$ 2,500.00	$ 2,500.00	$ 5,000.00
Total Intangible costs	$ 144,500.00	$ 60,200.00	$ 204,700.00
Tangible Cost	**Dry Hole 12- Days**	**Completion 7-Days**	**Total Cost**
Tubular goods-conductor CSG	$ 500.00		$ 500.00
Tubular goods-surface CSG	$ 4,500.00		$ 4,500.00
Tubular goods-intermed CSG			
Tubular goods-Liner			
Tubular goods-production CSG		$ 24,900.00	$ 24,900.00
Tubular goods-tubing		$ 12,900.00	$ 12,900.00
Tubular goods-flow lines		$ 2,000.00	$ 2,000.00
Tubular goods-other			
Casing Accessories		$ 500.00	$ 500.00
Downhole Equip-Packers			
Downhole Equip-pumps			
Downhole Equip-screen			
Downhole Equip-art. Lift			
Downhole Equip-rods/fittings			
Downhole Equip-tubing acc.		$ 500.00	$ 500.00

Downhole Equip-other			
Surface Equip-tanks		$ 8,100.00	$ 8,100.00
Surface Equip-separator		$ 3,500.00	$ 3,500.00
Surface Equip-dehydrator		$ 5,000.00	$ 5,000.00
Surface Equip-compressor			
Surface Equip-batt manifold		$ 2,000.00	$ 2,000.00
Surface Equip-wellhead/X-mas tree		$ 7,500.00	$ 7,500.00
Surface Equip-pumping unit			
Surface Equip-engine/motor			
Surface Equip-art. Lift			
Surface Equip-fittings/valve		$ 2,000.00	$ 2,000.00
Surface Equip-meter runs		$ 9,000.00	$ 9,000.00
Electrical equip.			
Contingencies		$ 3,000.00	$ 3,000.00
Total Tangible costs	$ 5,000.00	$ 80,900.00	$ 85,900.00
Total Intangible Costs	$ 144,500.00	$ 60,200.00	$ 204,700.00
Total Costs	*$ 149,500.00*	$ 141,100.00	$ 290,600.00

DRILL AND COMPLETE- UNDERBALANCED N2 -FLUID DRILLED

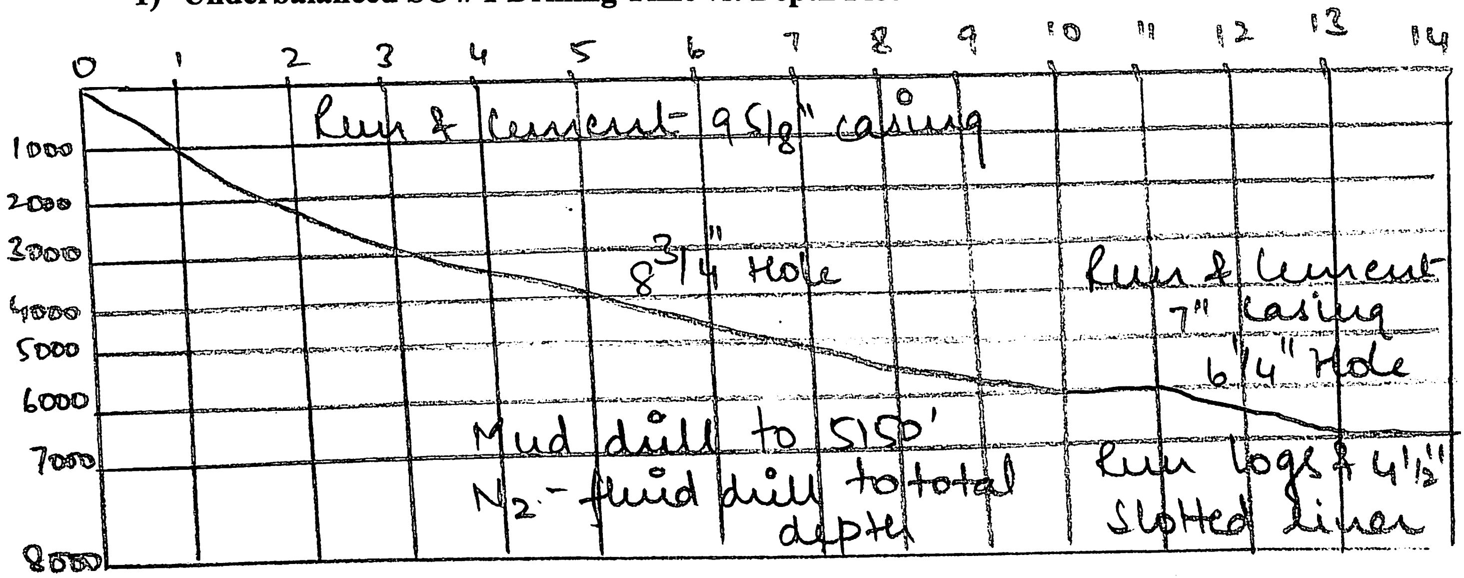
Intangible Cost	Dry Hole 12- Days	Completion 7-Days	Total Cost
Location- survey and permit	$ 400.00		$ 400.00
Location- road/maint.	$ 7,000.00		$ 7,000.00
Location- damages	$ 2,000.00		$ 2,000.00
Reclamation/P&A		$ 5,000.00	$ 5,000.00
Drilling rig- rig move	$ 6,500.00		$ 6,500.00
Drilling rig- contract	$ 63,000.00		$ 63,000.00
Drilling rig- turnkey			
Drill bits/stabilizers	$ 18,350.00		$ 18,350.00
Mud & chemicals	$ 10,000.00	$ 400.00	$ 10,400.00
Mud equipment			
Water- purchase/hauling	$ 12,000.00	$ 400.00	$ 12,400.00
Logging-mud			
Logging-open hole	$ 7,500.00		$ 7,500.00
Logging- cased hole			
Coring & analysis			
Testing & analysis			
Cementing-surface	$ 4,100.00		$ 4,100.00
Cementing- intermediate	$ 12,000.00		$ 12,000.00
Cementing- production			
Cementing- squeeze			
Rental-completion tools		$ 1,000.00	$ 1,000.00
Rental-other	$ 16,500.00		$ 16,500.00
Completion rig		$ 3,000.00	$ 3,000.00
Perforating			
Acidizing		$ 5,000.00	
Hauling/trucking	$ 4,500.00	$ 1,000.00	$ 5,500.00
Contract labor	$ 6,000.00	$ 8,000.00	$ 14,000.00
Prof. serv-geologist	$ 1,000.00		$ 1,000.00

Prof serv- engineer	$ 7,500.00	$ 1,500.00	$ 9,000.00
Prof. serv- drig. Foreman			
Prof serv.-other	$ 200.00	$ 700.00	$ 900.00
Admin. Fees-other	$ 2,700.00	$ 2,700.00	$ 5,400.00
Broker fees			
Misc. expenses	$ 1,500.00	$ 1,500.00	$ 3,000.00
Contingencies	$ 2,500.00	$ 2,500.00	$ 5,000.00
Total Intangible costs	$ 185,250.00	$ 27,700.00	$ 212,950.00
Tangible Cost	**Dry Hole 12- Days**	**Completion 7-Days**	**Total Cost**
Tubular goods-conductor CSG	$ 500.00		$ 500.00
Tubular goods-surface CSG	$ 5,000.00		$ 5,000.00
Tubular goods-intermed CSG	$ 38,625.00		$ 38,625.00
Tubular goods-Liner		$ 3,945.00	$ 3,945.00
Tubular goods-production CSG			
Tubular goods-tubing		$ 14,200.00	$ 14,200.00
Tubular goods-flow lines		$ 2,000.00	$ 2,000.00
Tubular goods-other			
Casing Accessories		$ 500.00	$ 500.00
Downhole Equip-Packers			
Downhole Equip-pumps			
Downhole Equip-screen			
Downhole Equip-art. Lift			
Downhole Equip-rods/fittings			
Downhole Equip-tubing acc.		$ 500.00	$ 500.00
Downhole Equip-other		$ 1,500.00	$ 1,500.00

Surface Equip-tanks		**$ 8,100.00**	**$ 8,100.00**
Surface Equip-separator		**$ 3,500.00**	**$ 3,500.00**
Surface Equip-dehydrator		**$ 5,000.00**	**$ 5,000.00**
Surface Equip-compressor			
Surface Equip-batt manifold		**$ 2,000.00**	**$ 2,000.00**
Surface Equip-wellhead/X-mas tree		**$ 7,500.00**	**$ 7,500.00**
Surface Equip-pumping unit			
Surface Equip-engine/motor			
Surface Equip-art. Lift			
Surface Equip-fittings/valve		**$ 2,000.00**	**$ 2,000.00**
Surface Equip-meter runs		**$ 9,000.00**	**$ 9,000.00**
Electrical equip.			
Contingencies		**$ 3,000.00**	**$ 3,000.00**
Total Tangible costs	**$ 44,125.00**	**$ 62,745.00**	**$ 106,870.00**
Total Intangible Costs	**$ 185,250.00**	**$ 27,700.00**	**$ 212,950.00**
Total Costs	***$ 229,375.00***	**$ 90,445.00**	**$ 319,820.00**

E) Underbalanced SC # 1 data analysis

1) Underbalanced SC # 1 Drilling Time vs. Depth Plot



2) Underbalanced SC # 1 Flow Rate (Zone 5200'-5220')

Lease Name **SC # 1**
State, County
Field Name

Pwf	**757**	**Psia**
BHP	**1,757**	**psia**
Drainage area	**160**	**Acre**
Well Bore radius	**0.26**	**Foot**
Net thickness	**20**	**Foot**
N factor	**0.7000**	
Reservoir Temp.	**123**	**F**
Permeability	**30**	**Md**

Skin factor	**0.00**	
Gas Gravity	**0.840**	
%N2	**0.00**	**%**
%CO2	**0.00**	**%**
%H2S	**0.00**	**%**
Condensate (yes)	**1**	
Res Temp.	**584**	**R**
Re	**1,490**	**Ft**
Viscosity gas	**0.0129**	**Cp**
Wconst	**0.4914**	
Pseudo	**Y**	**(Y or N)**
Z factor **gas rate**	**0.731** **313**	**Mcfd**

3) Underbalanced SC # 1 Flow Rate (Zone 5800'-5820')

Lease Name **SC # 1**
State, County
Field Name

Pwf	**960**	**Psia**
BHP	**1,960**	**psia**
Drainage area	**160**	**Acre**
Well Bore radius	**0.26**	**Foot**
Net thickness	**20**	**Foot**
N factor	**0.7000**	
Reservoir Temp.	**123**	**F**
Permeability	**30**	**md**

Skin factor	0.00	
Gas Gravity	0.840	
%N2	0.00	%
%CO2	0.00	%
%H2S	0.00	%
Condensate (yes)	1	
Res Temp.	584	R
Re	1,490	Ft
Viscosity gas	0.0136	Cp
Wconst	0.4914	
Pseudo	Y	(Y or N)
Z factor gas rate	0.722 332	Mcfd

4) Underbalanced SC # 1 Economic Analysis

Well Name **SC # 1**
Prospect

Gas Price	$ 1.50	($/gas unit)
Oil Price	$ 18.00	($/oil unit)
Working Int	1.00000	(fraction)
Revenue Int.	0.80000	(fraction)
---Gross—First		
Reserves	550,000	(gas unit)
Initial Rate	645	(unit/day)
Yield	0.02	(BO/Mcfg)
Prod. Tax rate	0.0700	(fraction)
Lease and	$ 0	
Drilling costs	$ 229,375	
Completion	$ 90,445	

Operating costs	**$ 1,235**	**($/MO)**
Drilling promot	**1.00**	
Time till drilled	**0.00**	**YR**
TIER 1	**TIER 2**	**TIER 3**
Risk Com- 100.00% letion	**70.00%**	**80.00%**
No. of Wells- 1	**0**	**0**
FNR	**$ 186,370**	
PW (10)	**$ 118,724**	
PW (20)	**($ 69,812)**	
PW (30)	**($ 33,358)**	
PW (40)	**($ 5,517)**	
PW (50)	**($ 16,171)**	
PW (60)	**($ 33,339)**	
Total Costs	*$ 319,820*	
First Year	**$ 201, 407**	**Rev**
Two Years	**$ 330,997**	**Rev**
Five Years	**$ 490,414**	**Rev**
Payout	**1.91**	**Yrs**
ROR	**42.40%**	
ROI	**1.58**	
DROI	**1.37**	

Comparison of Parameters

Typical #1 (Conventionally drilled) vs. Underbalanced SC #1

	Typical #1	UB SC #1
DRILLING COST, $	149,500	229,375
COMPLETION COST, $	141,100	90,445
TOTAL WELL COST, $	290,600	319,820
GAS RESERVES, MCF	550,000	550,000
OIL RESERVES, STB	11,000	11,000
INITIAL GAS RATE, MCFD	278	645
CONDENSATE YIELD, STB/MCF	0.02	0.02
PAYOUT, YRS	4.38	1.91
RATE OF RETURN, %	13.94	42.40
RETURN ON INVESTMENT, $/$	1.45	1.58
FUTURE NET REVENUE, $	130,635	186,370
PRESENT WORTH (10%), $	27,138	118,724

FINDINGS:

- The cost of drilling Underbalanced is nearly 1.5 times that of conventional drilling.
- Nearly $ 50,000 is saved upon by drilling Underbalanced due to the saving in Logging cased hole, cementing-production, completion rig & Tubular goods-production CSG.
- Almost $ 30,000 increase in the well cost by drilling Underbalanced due to increase in cost of the following: Drilling rig-contract, logging- cased hole, cementing- intermediate, rental-other & tubular goods-intermed CSG.
- Keeping the same reserves of Oil & Gas while drilling in both the cases, a nearly 3 fold increase in Initial gas rate, mcfd is observed while drilling Underbalanced thereby adding on to the economic feasibility.
- Pay out period is just half of the well drilled conventionally in the case of Underbalanced drilled well.
- A nearly 3 fold increase in the rate of return adds on to the benefit of drilling Underbalanced.
- Not forgetting that the present worth, which is the last parameter which is significantly high while drilling underbalanced which is nearly 5 times of the conventionally drilled typical #1.

Technology always has its own pros and cons and is accompanied by some limitations. The operator has to look into the various aspects before deciding upon any technology to be implemented in the field. The money invested brings fruition only when the recovery is improved. Though the initial investment of a well which is drilled Underbalanced is more in terms of the drilling and total well cost and present worth but looking at the significant increase in the gas rate, the payout period in years which is just half that of drilling conventionally, rate of return the benefits can be reaped very soon and hence Underbalanced drilling is the need of the hour and is an economically feasible proposal (if the conditions of operation are met).

Chapter 25 :

RISKS OF UBD

25. RISKS OF UBD

In this sense and keeping the two principle needs and conditions in mind there are certain risks involved in applying this new technology. The risk generally referred to is the broad measure of commercial success. Not only the short term but the long term results require investigation of many wells drilled both Underbalanced and overbalanced in the same formation and the same reservoirs in order to get some idea of how well the applied technology is working[22].

From a drilling risk perspective, many elements of risk are added over and above an overbalanced approach to drilling a well. A significant element of risk recognized in Alberta is the safety of the overall Underbalanced drilling operations. This has been summarized by the Alberta energy resources conservation board's (ERCB), now the Alberta energy utilities board (AEUB), perspective on the topic by the presentation of findings to date at the 1993 Canadian association of drillers and engineers (CADE) conference.

This work was instrumental in the formation of a joint industry drilling and completions committee (DACC) conference Underbalanced drilling sub committee. The result of this committee's effort was the preparation of the interim directive ID 94-3 "Recommended practices for Underbalanced drilling". This document which has been used as a guide in other provinces sets out the AEUB's requirements and application procedures for Underbalanced drilling operations in Alberta[22].

Since that time, improvements have been made in the overall process and the documentation with more wells drilled Underbalanced in different reservoirs and formation's including sweet and sour drilling operations. Because of the importance and success in implementing these Alberta recommended practices (ARP's) they will constantly be referred to in the risk analysis.

An additional challenge from the formation damage viewpoint and the benefits of Underbalanced drilling was raised by bennion et al, Hycal. They pointed out that the elimination of formation damage was "not" guaranteed with Underbalanced drilling systems. The ability of the Underbalanced drilling system to maintain an Underbalanced condition at all times was in question. The fact that the jointed pipe this condition could not be maintained there was a potential limitation to the overall system to prevent formation damage and certainly not 100% of the time. However they also acknowledge that underbalanced drilling had documented specific applications where severe well productivity impairment could be avoided.

Chapter 26 :

RISK APPROACHES

26. RISK APPROACHES

From the above discussion one has seen two approaches to using this technology. The first approach was the simplest and that was to follow the leader or the low risk approach for example let the competitor develop, improve and perfect the technique and then put your own team together to apply the improvements and findings to your own "look-a-like" applications. In other words when success is achieved by your competitor, the operation is duplicated in your own field. This methodology is appropriate when an operator can wait to apply the technology and the reservoir conditions are similar.

The second approach is to take on the role of "out front and first" to apply the technology. This could involve the use of a prototype drilling system but preferably would be a commercial system successfully demonstrated in another application. Because in any new technology being tried out in an experimental basis on a completely different set of circumstances the failure potential of such a system requires it to be recognized. Thorough preplanning and investigation has to be undertaken to understand the failure modes and minimize the consequences of their occurrence together with a flexible drilling program and data gathering system to ensure the maximum information is documented during the drilling operation[22].

The above approaches do not necessarily guarantee success, therefore a discussion of reasons for possible failure modes of the underbalanced drilling results are in order. The following are potential traps that one might fall into when considering underbalanced drilling technologies.

Chapter 27 :

ONE WELL DRILLING ATTEMPTS

27. ONE WELL DRILLING ATTEMPTS

When attempting underbalanced drilling as a new technology to exploit and extract hydrocarbons a total learning mind set must be employed from the team assigned in the pre-planning, equipment procurement and actual execution of the drilling phase and post mortem of the drilling operation to top level management who are providing the dollars to use the technology. In this regard one "should" not expect to have 100% success on the first attempt even with a flexible drilling program.

The function of every underbalanced drilling first time operator is to plan to capture extensive data in the drilling operation in order to improve and refine the system for future operations. Consequently a flexible multiwell program to evaluate and extract hydrocarbons in a developed field with horizontal underbalanced technology has a far better chance of success than a narrow philosophy that this narrow philosophy that this new and advanced technology is going to be the answer in a new exploration play. One must note that underbalanced drilling does not create permeability or hydrocarbons but is only another option in the driller's toolbox to be used to recover hydrocarbons.

It is unfortunate that many potential reservoirs have not been fully exploited using this technology because of the expensive perceived failures. Review and study of many wells indicate that the reason for the one well wonders not occurring has indeed nothing to do with the underbalanced drilling operation but some other piece of the puzzle that did not fit into the screening and operational criteria to ensure successful recovery of hydrocarbons from the reservoir.

UNDERBALANCED DRILLING PLANNING CHECK LIST:

Activity	Responsibility	Done
General		
Inform govt. of flare	Drilling superintendent	
Permit for drilling operation	Drilling superintendent	
Location preparation		
Identification of wind direction	Drilling superintendent	
Notification for wellsite preparation	Drilling superintendent	
Location preparation	Drilling superintendent	
Upstream side		
Equipment availability	Contractor	
Data acquisition	Contractor	
Downhole side		
Data collection	Contractor	
Risk analysis	Drilling superintendent	
Downhole equipment selection	Drilling superintendent	
EMWD	Drilling superintendent	
Air motors	Drilling superintendent	
Computer simulations	Contractor	
Bore hole stability	Contractor	
Torque and drag		
Underbalanced drilling program	Contractor	
Well killing procedures	Drilling superintendent	
Downstream side		
Fluid handling equipment	Contractor	
Data acquisition equipment	Contractor	

Chapter 28 :

RISK ANALYSIS

28. RISK ANALYSIS

A Combination of sensitivity analysis of the various possible scenarios of the behavior of the reservoir by the production technologists and risk analysis of the total operation by the drilling engineer shall be performed for these wells. Particular emphasis should be put on well killing operations for different scenarios. The risk analysis is considered critical for those wells with potential to free flow to surface or with a static fluid level close to the wellhead. The risk analysis of the total operation shall be generated up front by the project manager of the operation and passed onto the drilling supervisor.

Well killing practices should be augmented, for example with prior written kill sheets for the "worst case scenario", reaction times of the drill crew and surface equipment layout, pumping equipment, valves set up and adequate mud volume for the fastest well killing operation.

Chapter 29:

Conclusions

29. CONCLUSIONS:

A Detailed study on Techno-Economic aspects of Underbalanced over Overbalanced drilling was carried out and the following observations have been made:

Pre-screening of candidates involves ensuring that 'contra-indicators' to UBD are absent or manageable through proper design. The table above lists the main indicators, ie, good candidates for UBD, and contra-indicators.

Since one of the main premises of UBD is that it minimises formation damage from drilling, a critical step in candidate assessment is to seek clear evidence of damage and its implications on production. This involves a synthesis of different data sources and analyses: log evaluations, core analysis, drilling and workover history, production history analysis and prior analysis of well testing.

"It is important to speak with the asset team". "Finally, core calibration of dynamic damage modelling bridges the gap between empirical results and special reservoir simulation."

To establish UBD operability and technical feasibility it is necessary to conduct multiphase flow and mechanical modelling to help size and specify the equipment. Once the equipment and front-end costs have been estimated and cost-avoidance benefits and UBD deductibles identified, the risked inputs go into the cost model to produce P10, P50 and P90 cost estimates. The basis of the design for the well can now be developed.

*Once the reservoir value and the costs are estimated, they can be combined to obtain a risked NPV expectation for the proposed project. Ultimately, this provides the answer to the question "**is underbalanced drilling the right answer for your reservoir?**"*

From the Companies point of view:

1. The company has seen longer bit lives and bits coming out of the hole in better condition[23].
2. Wells drilled in the US were drilled for rate of penetration (ROP) benefits. They noted they only assume there will be any reservoir benefits and noted that they could not measure any reservoir benefits to date. Economics of development by underbalanced drilling is not known now. Also, any reservoir measurements they could believe are production and skin measurements.
3. Large service company- for companies now with experience in drilling underbalanced, sees operator motivation as ensuring a undamaged well is drilled, and increased productivity. For operators relatively new to using underbalanced drilling technology, the operators are looking for the advantage of having a drill stem test while drilling, increased ROP, or trying the technology because others have used it in their area of interest.
4. Economics was the primary motivator. These are driven by ROP and cheaper costs per foot. Underbalanced wells in these companies have never been done for production enhancement as a primary motivator. The company has not noted any production enhancements or productivity or PI enhancements with underbalanced drilling.
5. Noted that every underbalanced drilling operation has been more expensive than conventional operations by a big factor but on a $/foot drilled basis the tool economics may be less. Savings are dependent on operations, location and drilling environment.
6. Noted that improvement's in ROP has been the chief benefit. From a drilling contractor it has been a reduction of fluid loss and reduction of differential sticking. Operators tell them they are doing activity for reduction in formation damage.
7. The wells have been cost effective because fluid bills have been significantly lower than in overbalance drilling with this caused by less lost circulation.
8. The company noted that operators were drilling with air for:
    - Increase ROP-up to 85-90 ft per hour with air.

- Reduced formation damage by reducing formation exposure time
- Wells cost too much with fluid and are uneconomical
- Control of dogleg severity better with air drilling. An air hammer is used versus directional tools.

9. Underbalance application is a formation damage issue, although most of their applications do not involve much formation damage, like the chalk. The company is looking for applications for underbalanced drilling in depleted gas fields. To date they have had mixed success with gas fields, both low productivity and formation stability problems.
10. Drivers as 1) being economics, 2) increased reserves value by reduced drilling costs, and 3) technology is more reliable now and experiences are beginning to increase.
11. The other motivation for underbalanced drilling has been to drill through lost circulation zones.
12. Took a dying field and with underbalanced drilling it produces 10,000 barrels per day now.
    - Have seen a very favorable impact on ROP
    - Reduction in formation damage was primary reason. They believe they get better producers.
    - In pressure depleted reservoirs, it's the only way drilling can be done. Reduced lost circulation and pipe sticking. Reduced mud bills.

The company recently completed a program of 10 wells using underbalanced horizontal medium radius wells. They expected to see 3-5 million cubic feet per day but two wells produced at 20 million cubic feet per day gas rates. They penetrated better zones without formation damage. The verticals up to the time of horizontal drilling produced a maximum of 2 million per day.

13. As the company experimented with underbalance, they first started drilling at less overbalance, to at-balance, to underbalance, to more underbalance in progression. The underbalancing has been aerating fluids with either nitrogen or natural gas.

A company noted they were drilling underbalance to prevent formation damage on about half of their applications. The other half of the applications involved drilling in depleted reservoirs where a conventional overbalanced system would have large lost circulation problems. The company noted they are seeing these benefits:

- Not getting stuck as much
- Reduction of fluids losses to formation
- Reduced problems with counter current imbibition resulting in tripling of production
- Increased productivity on a case with drilling at balance and had 50% higher production than offset wells

14. Better ROP is main reason. Wells drilled principally with air take 6 days versus 20-25 days with a mud type system. They noted:

    - Shorter number of days with reservoir exposed
    - Better gauge hole. No sloughing in of hole. Better cementing jobs (no muds in front of cement job and hole is in clean shape)
    - Reduced fluids bill
    - Formation damage is less. A differential pressure into the well would cause migrating and swelling clays problem for the company. On over 99% of their wells, they are stimulating the wells after drilling by acid fracing the wells. Formation damage is not as much of an issue because wells are stimulated. Formations are tight at about 0.5 md or less.
    - Measurements of flow rate is available in underbalanced drilling so can obtain a type of drill stem test.

15. The operator is seeing if an underbalanced horizontal well will reduce water coning versus an overbalanced horizontal well. The hope is with less damage, drawdown is minimized making a more effective horizontal well. They plan on looking at productivity and production numbers to understand this area.
16. The company noted that underbalance has caused higher ROP because drag is minimized, and hole cleaning has been good for them. In some instances they have been able to evaluate the reservoir as they drill the well, and this helps in the completion phase[23].
17. Company saw the benefits when they started underbalanced efforts as:
    - Reduced formation damage
    - Better evaluation of the reservoir when drilling through the reservoir rock
    - Increased ROP
    - Economic improvement and expense savings in drilling

Thus I conclude that: Of those benefits, the company saw only ROP increasing at least 2 to 3 fold. For the other areas, the company was still looking for proof. They had no quantitative proof of the advantages. The problem in comparing is that there is so much viability in the rocks, fluid saturations, and other factors, that they have been unable to compare results correctly. In the fields they were operating, some wells would be quiet good producers, and other was not as good producers. In one field they believed they needed 20 underbalace wells to properly assess the benefit. Also, is the measure a formation damage or formation quality issue? Skins are calculated and inputs to the calculations have large variances. So, their initial reasons to keep using the technology were ROP, while working on improving the technology and try to get the other targeted benefits. One of the objectives was to get costs down to overbalanced well operations and look at the technology for the long term.