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Optimizing Reservoir Characterization During Underbalanced Drilling: Tools, Analysis Methods and Results

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Abstract

Underbalanced drilling (UBD) provides engineers with the opportunity to quantitatively describe and evaluate each geologic zone as it is penetrated. This provides them with the flexibility to adjust a drilling program still in progress if warranted by confirmed reservoir characteristics. UBD is different from conventional drilling in that all reservoir intervals are tested automatically while drilling, whether or not they are believed to contain commercial volumes of hydrocarbons at the outset. By drilling in a UB mode and by maximizing the discrete characterization of each formation, many instances have occurred in which zones previously thought to be uneconomic—or missed altogether by available modeling and planning data—have been found to contain reserves adequate to justify completion.

Introduction

This paper describes the basis of analysis for this reservoir evaluation process, the analytical methods that have been developed and used in the field to determine reservoir properties such as permeability, reservoir pressure, skin damage - if any and reservoir extents (extent, will depend upon whether there is sufficient time to see influence of boundaries) for each zone drilled based upon history matching. A key enabler to performing analysis while drilling has been the ability to obtain the mathematical solution to the moving boundary condition problem. In conventional well testing, the length of the wellbore open to flow is constant, since it is assumed that the well has already been drilled; in UB drilling, however, obtaining a solution is more complicated, because the length of the wellbore open for flow increases as the well is being drilled. This problem has been solved and has been implemented in software for easy application. A case history will be described comparing conventional and UBD results as well as well testing while drilling.

Underbalanced drilling provides both drilling and reservoir benefits including the following:

- Reduced formation damage
- Early production recovery while drilling
- Formation evaluation or “testing-while-drilling”
- Identification of production zones (if oil, optimize; if water, shut-off).
- Identification of natural fissures as they are intercepted
- Determination of total depth (TD) based on inflow performance
- Improved PI completions
- Improved Rate of Penetration (ROP)
- Extended bit life
- Minimization of differential sticking
- Reduction of lost circulation.

Unlike conventional overbalanced drilling or even managed pressure drilling (MPD) with reduced overbalance margin, the underbalanced drilling environment provides a unique opportunity to gather data that have the potential to provide important information about the reservoirs encountered during drilling. In underbalanced drilling, the wellbore pressure is lower than the reservoir pressure. This wellbore condition allows formation fluids to flow into the wellbore during the drilling process. Proper instrumentation, data acquisition, and drilling procedures allow acquisition of data that is then interpreted and analyzed to extract information about the reservoir.

Subsequent well operations have the potential to cause damage to the reservoirs that have been opened to the wellbore during drilling. To evaluate these reservoirs in an undamaged state (or as close to undamaged as possible) requires capability to evaluate the data acquired during the drilling process. During underbalanced drilling the data can be accessed when the reservoirs are first encountered and analysis performed with the formation fluids flowing into the wellbore. Results such as reservoir permeability from this evaluation allow the operator to determine the potential of each productive interval encountered during drilling. These results, when integrated with logging-while-drilling data and other geological, geophysical, and petrophysical data, can provide a more complete reservoir characterization than would have been possible using conventional drilling and formation evaluation techniques.

The reservoir-related or production-related benefits of UBD are quite significant when compared with conventional overbalanced drilling (OBD). Primarily, these benefits are seen through higher productivity of UBD wells, and in some cases, improvement in hydrocarbon recovery factors and added reserves. These latter benefits can be due to either:

1. improved well-reservoir connectivity and avoidance of

near wellbore impairment, which allows lower abandonment pressures
2. the discovery of a productive interval that had not appeared to be productive during overbalanced drilling.

Underbalanced Drilling Candidates

Proper candidate selection is critical to the success of UBD projects, especially when these projects focus on the reservoir. It is essential that the main project objectives are identified at the beginning of the project to ensure that they can be achieved.

The candidate selection process consists of analyzing the drilling, geological, reservoir, geomechanical and petro-physical information to determine whether a particular well and/or reservoir is a potential candidate evaluating some of the main reservoir and wellbore characteristics. These include:

- the type of formation damage
- the possible effect of UBD on its mitigation
- wellbore stability
- potential for stuck pipe
- hard rock drilling
- possible rate of penetration (ROP) improvement
- lost circulation problems
- presence of sour gas
- operational feasibility.

Preliminary wellbore-hydraulics modeling is performed to determine the operational feasibility; i.e., if underbalanced (UB) conditions are possible and can be maintained throughout the entire hole section while maintaining adequate hole cleaning and satisfying the downhole motor constraints. If there are multiple candidates, characteristics of each of these would be compared, and an initial ranking would be performed, and then ranked according to the key variables that would have the highest potential for success.

Reservoir Characterization Candidates

To perform reservoir characterization while drilling, it is important that the system remain underbalanced throughout the operation. It is important to note that while it is possible to perform reservoir characterization while drilling under-balanced with some short periods of overbalance, it is not possible to do this with overbalanced drilling or managed pressure drilling (MPD) because of the deliberate suppression of reservoir influx during these operations. Even if the system is kept in an at-balance condition, the pressures would be fluctuating above and below the formation pressures, making it difficult to clearly identify and characterize the properties of the productive intervals; This is due to the fact that it would not be possible to determine what section in the open hole being drilled is producing when and in response to what corresponding drawdown pressure.

Potential candidates for real-time reservoir evaluation can often be distinguished by several key questions. These include:

1. Is there poor knowledge of reservoir properties (permeability, *k*, Reservoir Pressure)?
2. Is there poor knowledge of productive zone location?
3. Are good formations seen on logs, but no or very poor production noted when formation is tested?
4. Are the formations depleted or classified as a brownfield or a mature field? If so, is there a need to know where flood front is (if break through has occurred) or to identify locations of high permeability that are allowing early break through and inefficient flooding?
5. For conformance, is their a need to determine the location of a high water-production zone for optimization of conformance treatment?
6. Is the formation naturally fractured and would it be useful to determine location and potential of fractures or “sweet spots”?
7. Is there an interest to determine whether 1) a shorter lateral or drilled interval will meet the production targets by testing productivity while drilling, and 2) should sustained rates and possible depletion, be determined (if sufficient time is given)?
8. Is interconnectivity of zones in different wells of interest to be tested while drilling UBD?
9. Is there high formation damage seen while drilling conventionally, and is there an interest in determining the undamaged potential of the formation while drilling?
10. Has stimulation proven ineffective in the target reservoir, and would another possible technique be useful to evaluate possible productivity?
11. Is the formation very tight requiring stimulation, and would characterization of the formation be helpful to optimize the stimulation treatment?

If a prospect proves to be a candidate from a technical standpoint, it is also important to consider the economic aspects and determine whether the cost savings from reduction in non-productive time (NPT), savings from mobilization of a separate well testing kit (conventional), and possible revenue from potential production improvement as well as reservoir knowledge would justify the added cost of UBD.

Tools and Analysis Methods

Development

Reservoir characterization while drilling began to gain recognition as a testing option in the 1990s as rate and downhole pressure data were observed to be of sufficient quality for transient analysis. Several investigators looked at different means to perform this type of analysis including Kardolus, van Kruisjdijk, Larsen, Nielsen, Kniessel, Rester, Hunt, Biswas, Vefring et al.[1-6] Reservoir characterization-while-drilling methods and software development described and used in this paper began in earnest in 1998 with the development of a model for the moving boundary condition seen while drilling and implementation and testing of the model.[3,7] From the initial analytical model for a vertical well in a circular reservoir, the development grew to handling of any reservoir or wellbore geometry. Currently, both an analytical model and numerical simulator are used. Both allow the handling of a range of complexities from simple well and reservoir geometries with single-phase flow all the way through complex multilaterals in a complex fractured reservoir with multiphase flow in the reservoir.

Similar to a conventional well test, the reservoir evaluation process during underbalanced drilling monitors the rates, pressures, temperatures, depths and fluid properties, and uses this data to characterize the permeability, reservoir extent (if sufficient time), reservoir pressure, PI, or fracture properties of the zones drilled. From comparison with conventional well testing, it has been found that the radius of investigation is similar to other well tests and depends on the formation properties and the time spent producing from that particular zone.[8] If underbalanced conditions are maintained throughout the operation, it also provides an opportunity to review the undamaged reservoir potential, which in some cases, reveals productive intervals missed when drilled conventionally and a quantification of their contribution. If, per chance, the system goes overbalanced, then skin damage can also be determined using the analytical and numerical simulators developed for well testing while drilling.

Analysis Methods

The reservoir characterization-while-drilling process begins several months prior to the operation in conjunction with the engineering design and job preparation phase. At this time, offset data and information are obtained from the field's geologists, reservoir, and drilling engineers to build a model of the reservoir and estimate expected reservoir behavior while drilling underbalanced for different possible scenarios. As mentioned above, wellbore hydraulics will also be modeled to ensure that underbalanced conditions and hole cleaning can be maintained with the expected influx. Then, the testing procedures are developed for all productive formations and discussed with the project team to ensure that objectives will be met within the time and operational constraints of the project.

The required data are transmitted while drilling underbalanced through the reservoir intervals, and these data are reviewed and quality controlled prior to analysis. The first step is to calculate the sand-face rates downhole based on the rates measured at surface. The calculations must take into consideration the time lag and transients in the wellbore. These data are fed to the pressure-transient analytical model, and, in cases where the system is complex, to the UBD numerical simulator.

Reservoir characterization requires an integration of all the data sources to minimize uncertainty and non-uniqueness of a solution; therefore, access to well logs, mud logs, and fluid characterization during the operation is key, and this information is integrated with the transient analysis results.

Analysis Tools

The analytical software developed for pressure transient analysis for Real Time Reservoir Evaluation (RTRE™) while drilling underbalanced differs from conventional pressure transient software. There is a significant difference between multilayer models available in the literature for well testing [9,10] and models for underbalanced drilling, since with UBD, the model needs to consider the increasing wellbore length, which could traverse different productive formations that have different characteristics. Each of these intervals would be drilled and open to the wellbore at a different time. Additionally, each zone would be partially penetrated for a period of time until another zone was reached. In contrast, the well is essentially static with respect to wellbore geometry for conventional well testing, and production commences at the same time once the well is put on production. Rester and Hunt[7] described the initial model that was developed to address these issues. The current model has been expanded further as described by Ansah et al.[8]

With this model, the reservoir initial pressure, permeability, thickness, and boundary (if seen) can be determined for each layer drilled. Different reservoir outer-boundary conditions are modeled including infinite, radial, one-boundary, two-vertical boundaries, etc. for either homogeneous or naturally-fractured reservoirs. In practice, it was found that during underbalanced drilling, overbalanced (OB) events, resulting in skin damage, can occur. It was found that a multiple damage model was needed to quantify this damage (skin factor).

The analytical simulator has proved very useful and applicable to most reservoir scenarios encountered; however, it was found that a numerical simulator was needed in some cases. An analytical simulator is limited to simple wellbore and reservoir geometries and to single-phase flow in the reservoir. Thus, the UBD numerical reservoir simulator used is a full 3-dimensional, 4-phase, non-isothermal, pseudo-compositional, multi-well reservoir simulator. By history-matching rates and pressures, formation properties for the zones traversed based on the optimum match between the measured and predicted 3-phase flow of oil, gas, and water from the reservoir into the wellbore while drilling. The numerical simulator is capable of simulating multiple layers with varying layer properties (i.e. porosity, thickness, initial pressure). Additionally, it accounts for the moving boundary problem (increasing well length) for complex wellbore geometries including multi-laterals within complex reservoirs with complex outer boundaries. Multiphase analysis of reservoirs with complex fluid systems (volatile oils, gas, condensates, etc.) is performed and non-Darcy effects - can be modeled. The simulator allows for better representation of non-conformities, and fractures compared to the analytical model, although like the analytical model, a dual-porosity model and discrete fracture model are included.

At the present time, a downhole rate-measurement tool that can accurately obtain the influx rate and pressure at the reservoir sandface downhole has not been developed. This means that while the pressures are accessed downhole with a pressure while drilling (PWD) tool, the rates are measured at surface. The lag time and transients in the wellbore must be considered using wellbore hydraulics software. Some attempts have been made to link the reservoir model and the wellbore hydraulics model, however, either one of the models must be overly simplified to allow timely convergence and calculation time, or alternative numerical methods such as neural nets can be used to minimize the complexity of linking two transient simulators.

Data Acquisition Requirements

The zone-by-zone characterization with UBD is only possible by using systems with adequate bottomhole -pressure control, fluids and solids separation, metering, and data-acquisition systems (DAS).

A DAS system that performs very basic operations primarily used for monitoring the system for safety or very limited data gathering may have a limited number of channels. In terms of analysis, this would be considered a basic level of analysis where the instantaneous “pseudo” Productivity Index (PI) is sought for a UBD operation.

For performing reservoir characterization while drilling underbalanced, more data will be required, and typically, a 100 to 120-channel data acquisition system may be used with a data-management system that has been specifically configured for that underbalanced operation.

If reservoir characterization is required for underbalanced drilling, then a total data-management software would be required to provide the capability to integrate all worksite well information from whatever source for real-time display and data manipulation at the rig site, and optionally, in the client office via a wide area network (WAN) system.

A system for reservoir characterization in UBD would require capability to monitor all pressure, temperature, fluid levels, and flow-rate information normally associated with the surface separation package. It would also need capability to accept, manage, store and display other rig-site data such as measurement while drilling (MWD), logging while drilling (LWD), surface data logging (SDL), etc., which are generally integrated by the data-acquisition-and-management system via the Wellsite Information Transfer Specification, (WITS) protocol. This collected data are viewed historically or in real time via XY plotting, charts, and logging tools.

Field Case

Background

A recent underbalanced drilling operation was initiated when conventional overbalanced drilling (OBD) resulted in severe losses, and it was found that to minimize non-productive time, another solution would be required. Conventional lost–circulation-control techniques proved inadequate, as after large quantities of lost-circulation material were pumped in an effort to block what appeared to be a major fracture, the drill string became stuck. Underbalanced drilling was considered as a potentially more economical option compared with the cost of time and fluids required to drill overbalanced (OB). Also considered was the possibility that underbalanced drilling would be more capable of allowing the hole to reach the target successfully. Other wells drilled in the area generally produced in the range of 8 to10 MMScf/d after some type of stimulation treatment. Prior to stimulation, the production ranged between 2 to 5 MMScf/d. The area is highly stressed, resulting in faulting and fractured formations. Some of these faults can form sealing barriers, which were thought to result in possible compartmentalization. Sufficient data were not yet available to confirm that this was the case. It was thought that the reservoir was still close to the original reservoir pressure, although there was the potential for varying pressures if multiple compartments were traversed. Offset wells and seismic information indicated that there might be a well-developed fracture network composed of macro-fractures parallel to the faults and micro-fractures interconnecting any available porosity.

Project Drivers

The primary objective of the well was to solve the drilling problems by safely drilling to the target depth while maintaining pressure control at all times and minimizing fluid losses. The secondary objectives were to minimize reservoir damage and evaluate the productivity of the different reservoir intervals, characterizing their properties from flow testing, determining production sustainability, and finally, if stimulation would be needed.

By drilling underbalanced, all objectives were met successfully; and it was possible to drill into the reservoir section without any losses. The well did not reach the target depth due to unexpectedly high production rates (**Fig. 1**), making it unfeasible to drill further underbalanced.

Results

When comparing underbalanced drilling with overbalanced drilling in this field, savings in several areas were noted. These included a reduction in nonproductive time (NPT), bit runs, number of bits used, savings on mud, and stimulation costs. NPT from conventionally overbalanced drilling resulted in time spent controlling the well and dealing with stuck pipe, which was approximately 4 times more than the average time it took for drilling underbalanced. As for bits, typically 6 to 8 bits were required for the high compressive-strength rock when drilling overbalanced in this interval. During underbalanced drilling, only 3 bits were used for this well.

However, what made this project remarkable was the production improvement seen in the underbalanced wells. This magnitude of improvement had not been seen in the offset wells drilled OB, since the formation was found to be very sensitive to damage.

Looking at the plot in **Fig. 2,** it can be seen that consistent peaks in flow rate, which in most instances correlate very well with the decreases in bottomhole pressures. There were two shut-in periods — one at 0.6 days and the other commencing at about 2.6 days.

Prior to the second shut-in, a multi-rate test was performed. Optimally, during each rate step the bottomhole pressure should be kept as constant as possible. It can be seen that the bottomhole pressure was pretty constant for each step; however, some variation was observable in the measured rate data at the start of each step as the transients in the wellbore adjusted to the new gas and liquid-rate combination. For this well, drilling fluid was injected at a constant rate with no gas injection necessary. The reservoir pressure was sufficient for flow drilling (where underbalance is achieved without gas injection). Typically, a 3-step multi-rate test is recommended as seen in this case. For this well, it was possible to perform both multi-rate tests as well as buildups, and the results were analyzed and were in good agreement.

To determine the formation properties of the intervals drilled, different reservoir models were needed; the first zone that was encountered was produced from the matrix, while a naturally-fractured dual-porosity-fracture model best described the rate/pressure behavior of the second and third productive intervals.

The predicted gas-flow rates were matched with the measured gas rates using the downhole pressure data as input and tuning the value of the permeability-thickness product, *kh*. The actual reservoir pressure had been estimated initially based on the data acquired while drilling and was then verified with the multi-rate test and buildup data.

The production improvement seen with underbalanced drilling showed approximately a 10-fold increase over the sustained offset overbalanced well rates and a 5-fold increase compared to the best stimulated well in this and an adjacent concession.

Another important advantage gained was the opportunity for reservoir characterization that only UBD allowed. The reserves of this field had not been confirmed, and this confirmation became a primary objective for the next UBD wells. Logging, PLT, and long-term production tests confirmed the characterization performed while drilling.

To determine the reservoir characteristics while drilling in this UBD well, the equipment setup shown in **Fig. 3** and data acquisition setup illustrated in **Fig. 4** were used with a high-end data acquisition system and additional metering for the gas rate. It was possible to have both a PWD and downhole memory gage to obtain bottomhole pressure, which allowed verification of this very important parameter. Two different types of gas meters, which provided verification and cross-check of the gas rate at all times, were used. The acquired data were sent via a satellite transmission system to the reservoir evaluation center, where the analysis of the data was carried out in real time. As mentioned above, periodic flow tests and pressure build-ups were conducted along with the normal analysis of the data acquired while drilling ahead.

Throughout the drilling of the underbalanced well, the rate and pressure data were analyzed, and the formation properties determined. In **Fig. 2**, an excerpt from the data that has been normalized is shown. The bottomhole pressure, actual measured rate, and calculated predicted rate using the underbalanced analytical software are shown. It was determined that multiple zones were responsible for the production seen, one of which had not been productive previously when drilling had been overbalanced.

The permeability, height, reservoir pressure, reservoir extents, PI, and skin damage (due to period of overbalance) were calculated for the different zones. Two of the intervals exhibited behavior best described with the naturally fractured model, and these fracture properties were calculated. In addition to the normal analysis of the production-while–drilling data, periodic flow tests were conducted to substantiate inflow potential along with determination of associated fluids production as can be seen in the plot. The flow tests were conducted while circulating fluid down the drill string and monitoring bottomhole pressure with the PWD. Stimulation treatments were not required, further proving that added cost savings can be generated from drilling with underbalanced techniques.

Conclusions

A method using a multilayer reservoir model to analyze flow-rate data acquired during underbalanced drilling has been presented. This process was demonstrated on an example dataset based on actual data from a field case.

Using the multilayer reservoir model to analyze data acquired during the underbalanced drilling process provides a more complete reservoir characterization than would have been possible using conventional drilling and formation evaluation techniques. The characterization is further enhanced when integrated with existing geological, geophysical, petrophysical and engineering data.

In attempting to perform reservoir characterization while drilling underbalanced, it is not possible to separate out the different aspects associated with each discipline such as can be done with conventional drilling, where after the geologists and reservoir engineers determine the best location to drill, the drilling group drills the well,; then, the well is turned over to completions, then testing, and production operations. To optimize the underbalanced drilling operation and maximize the knowledge gained from reservoir characterization while drilling underbalanced, input from all the specialists involved and integration of the other data acquired is necessary to cross check results.

The primary reason for conducting well tests while drilling is the capability to obtain reservoir engineering information about each of the zones traversed, layer by layer. Each zone tested during underbalanced drilling yields information about possible near wellbore and reservoir boundaries as well as reservoir connectivity throughout the field. Testing-while-drilling provides an opportunity to identify additional zones that potentially might affect the completion strategy for the well.

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SI Metric Conversion Factors

°F	(°F - 32)/1.8		=°C
ft	x 3.048*	E - 01	= m
in	x 2.54*	E + 00	= cm
psi	x 6.894 757	E + 00	= kPa
gal	x 3.785 412	E - 03	= m3
ft	x 3.048*	E - 01	= m
bbl	x 1.589 873	E - 01	= m3

*Conversion factor is exact.

Fig. 1— Field case showing gas flared during the UBD operation.

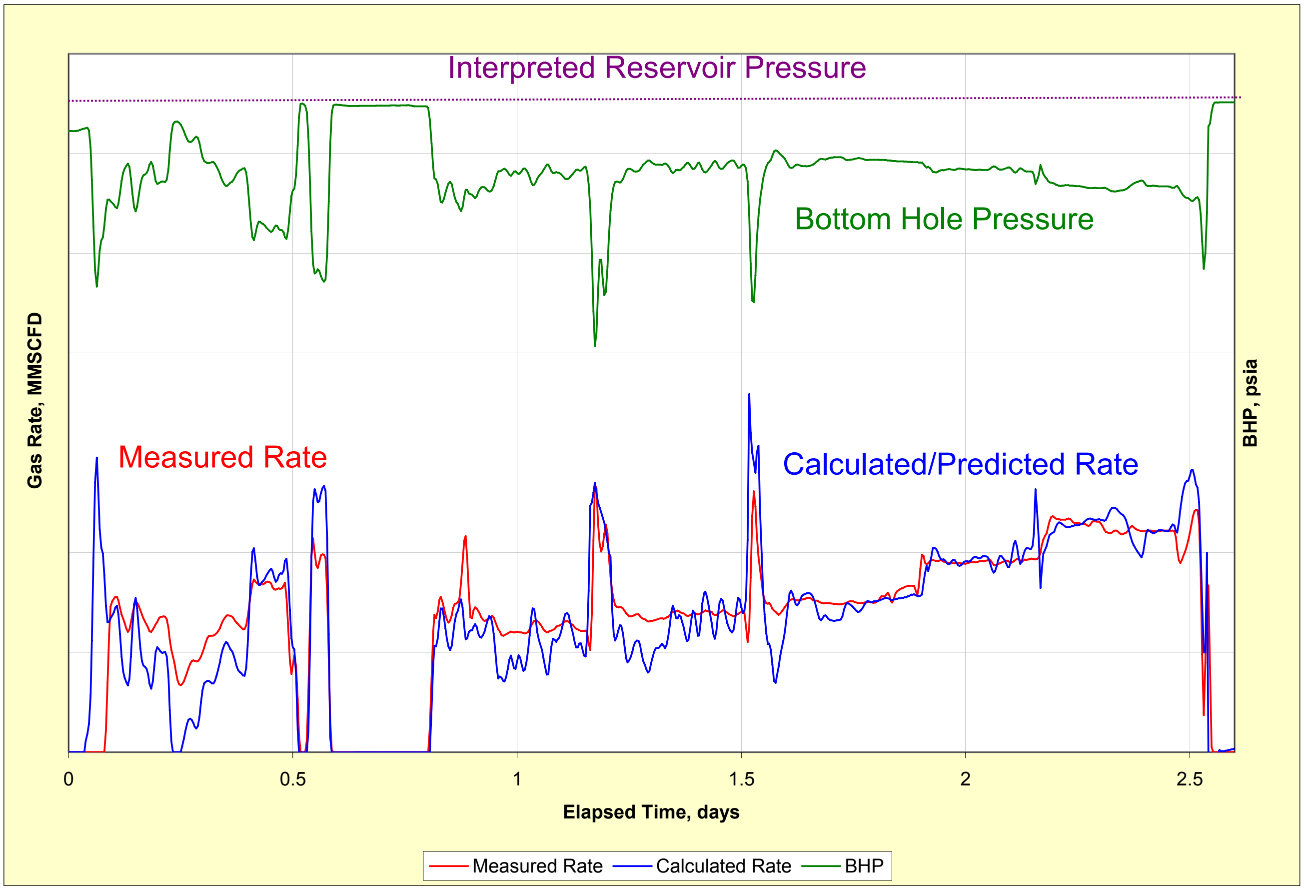

Fig. 2 — Analytical results showing predicted and measured rate along with measured bottom hole pressure.

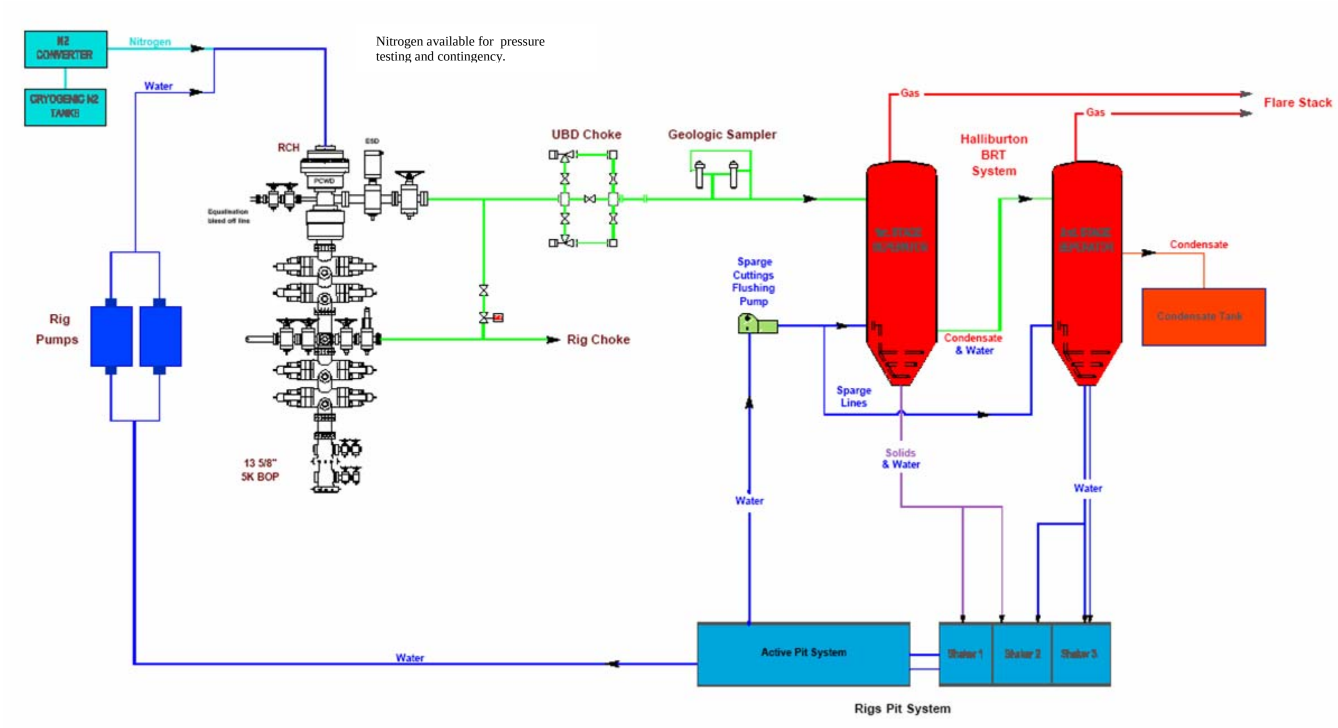

Fig. 3 — UBD Equipment Setup.

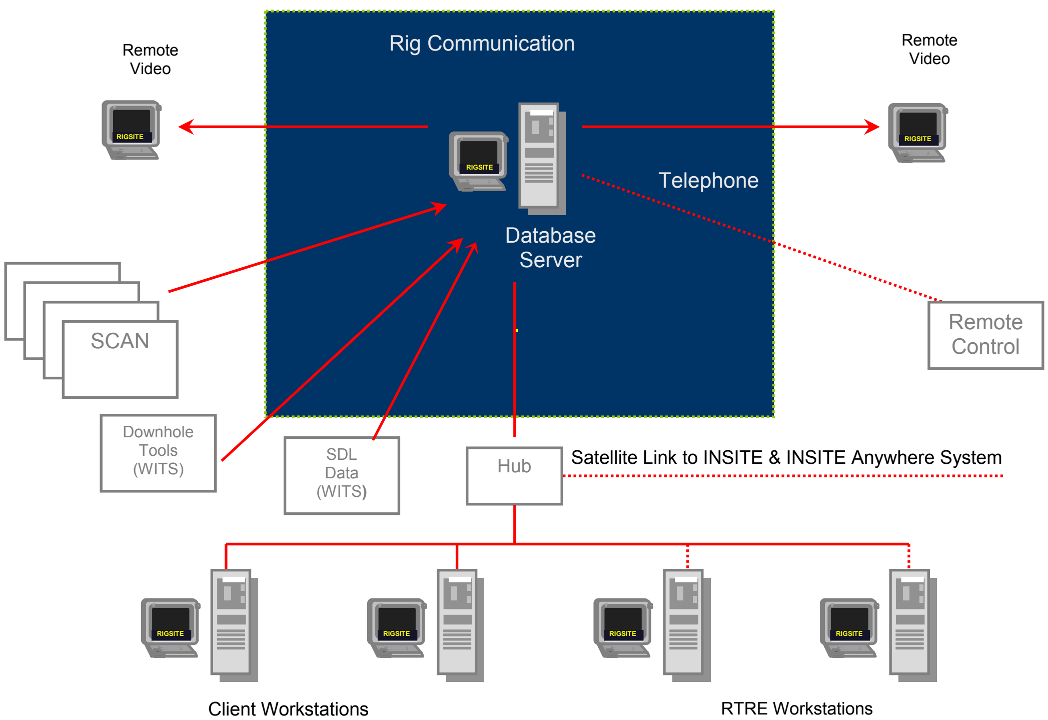

Fig. 4 — Data Acquisition Setup.