Wells drilled in ultra high-temperature, high-pressure environments (UHTHP) must be planned, drilled and produced using significantly less formation data than their shallower and cooler counterparts. As a result, operators must rely on pre-drill estimates of key formation properties – pore pressure, stress and rock strength – to plan and drill these highly challenging wells. This paper examines how the accuracy of the estimates can be improved, while drilling, using other data readily available to the driller. This process will help assure borehole integrity and contribute to reduced well costs.

Introduction

There is considerable interest in deep geologic horizons, especially in areas like the GOM and North Sea where production infrastructures are well established. With these depths will come ultra-high pressures and temperatures ranging as high as 30,000 psi and 500ºF. Among the many challenges for drilling such wells perhaps the most important is the ability to maintain well control. In a study commissioned by the U.K. Health and Safety Executive in 2005, well control incidents are by far the most frequently occurring of all HTHP well safety concerns. According to the report, “the main issue is the high-pressure regime that exists in the prospective zone and more specifically the narrow margin between the required borehole pressure to control the reservoir pore fluid pressures and the allowable pressure to retain borehole competence” (see figure 1).

Estimating Borehole Pressure

The current state-of-the-art for pore pressure estimation is to construct a pre-drill geomechanical model that integrates seismic interval velocity data and information from offset wells with the basin geological model. Since in-situ pore pressure is a function of how overburden stress, compaction and sealing mechanisms developed over time there is particular emphasis on reconstructing the basin’s depositional history.

This pre-drill model is then updated during drilling, relying primarily on MWD and LWD measurements, with mud logging data and drilling reports taken into account. This methodology, when applied correctly, yields very effective recommendations for mud weights necessary to maintain the well within safe operating parameters. Modeling alone cannot eliminate risks inherent in managing pore pressure in UHTHP wells. However, substantial gains can be made by a program combining qualified people, process and technology, operating planning, surveillance and knowledge management strategies. In such programs well control incidents are greatly reduced. In addition to the safety benefits, this strategy can result in shorter drilling times and reduced mud costs.

Data Limitations in UHTHP Wells

UHTHP wells will contain some of the most hostile drilling environments ever encountered. Their pressure and temperature profiles are well beyond the limits of current LWD technology and at the upper limit of wireline tool specifications. Operators should anticipate that data from sonic logs, pressure-while drilling and resistivity tools will either be unattainable, unreliable (due to high failure rates) or prohibitively expensive. Even if logging companies expand the operating envelopes of their tools
to cover UHTHP specifications availability will be tight, operating lives will be short and tool size selection will be limited. Based on studies conducted by a major LWD provider, operators are reluctant to use complex LWD arrays even when tools available of the required size, temperature and pressure specifications are readily available.

Pore Pressure Estimation without LWD

In the absence of LWD data, pore pressure estimates must rely solely on the accuracy of the pre-drill geopressure model, updated and recalibrated with information available from drilling processes alone. This alternative to LWD/Wireline-based pore pressure estimation is illustrated schematically in figure 2. Although fairly new, recent advances in geomechanical modeling are producing very promising results for real time modeling without the use of LWD data.

Such operations are not unprecedented - typically, this has occurred where operators have chosen to eliminate the high cost of LWD service, or where LWD data was found to be unreliable. Poor tool performance is not the only cause of unacceptable or misleading log data. Environmental influences on logging measurements can introduce significant errors into pore pressure estimation. This is especially true where sandstones, carbonates, and other nonclay-rich rocks are prevalent. Another downside of log-based pore pressure analysis is the tendency to over-rely on such measurements as borehole sonic velocity. In some cases the data is accepted as if it were a direct, definitive measurement of pore pressure, disregarding other available drilling data that is contradictory. This can introduce systemic errors in the pressure estimation process that are compounded as the well is deepened. Finally, in many cases the bottom-hole assembly is located 100 or 200 feet above the bit, so the information does not reflect true bottomhole conditions.

There are three components to the pore pressure prediction process – the Basin Study, the pre-drill predictive model, and real time updating, summarized as follows:

**Basin Study**
- A geomechanical model is developed that incorporates information throughout the basin. The parameters of the model include water depth, age, thickness, lithology, water saturation, geothermal gradient.
- A forward model is run to develop a burial history.
- The modeled results are matched to petrophysical controls at each well, and spatially smoothed to yield an interpretable surface that fits known pressure and porosity data in the basin. A thorough explanation of this process is available in a paper by Messrs. Williams and Madatov.

**Pre-drill Pore Pressure Predictive Model**
- The calibrated model is integrated with seismic to adjust for local anomalies such as faulting and salt diapers.
- The integrated model is used to prepare a pre-drill pore pressure prediction for the entire well profile.

To verify the methodology, a Joint Industry Project (DEA119) was conducted in 2003-2004 for five basins in the Gulf of Mexico and the North Sea. For 62% of the wells, the predicted pore pressure was within 1 pound per gallon (ppg) over the entire length of the wellbore. For 38% of the wells the prediction was within 0.5 ppg.

**Real-time Model Updates**

To provide the level of accuracy required to support well construction, real-time updates of the model are needed while the well is being drilled. This entails that a geomechanics analyst be assigned to the project. Until fairly recently real-time pressure updates were not generally feasible because of the high level of computational and subject-matter specialization required. Typically, the analysis was expensive, highly technical and reserved for only high-profile, high-risk wells, especially deepwater. The analyses were costly, and results relatively slow to obtain, and thus impractical.

However, recent advances in modeling techniques allow the analysis to be done on a laptop. Model complexity has been reduced with a strong emphasis on getting actionable recommendations into the hands of the drilling decision-makers: on time, understandable and at a reasonable cost. This has opened up the modeling to personnel who have a broader general knowledge of the realities of day-to-day decision-making in a drilling environment. To be effective, this process has several key attributes:

1. Personnel involved must be informed in advance to understand the importance of the process their role in providing and using information.
2. A clear understanding of the communications lines between rig-based data providers, the pore pressure analyst, corporate drilling engineering staff and rig-based decision-makers/implementers.
3. Pressure analysts must have a strong working knowledge of rig environment, both for the equipment used and the need to communicate information in an unambiguous and timely manner.
4. Flawless performance of the data transfer and
management systems. Standards such as WITSML should be adapted to ensure data integrity.

Building Models without Logs
The key to real-time modeling downhole pressure without LWD or wireline data is to start with a robust geomechanical model, then to extract as much pressure-related information as possible from all available drilling parameters.

The useful data falls into 3 major categories:

- **Drillstring Mechanics** - information derived from the mechanical performance of the drillstring in its interaction with the wellbore provides information on hole conditions and rock strengths
- **Fluid System Hydraulics** – because the mud system interacts with in-situ pore fluids and exerts hydraulic forces on the formations it transmits information about in-situ pressures. These can be observed in flowback time and volume comparisons.
- **Fluid System Contents** – largely provided by the mud logging system, such as cuttings analysis and gas content provides a wealth of information about downhole lithology and pressure conditions

This methodology has been applied using only commonly-available drilling data from drilling equipment meters and sensors, the daily drilling report and the mud logging systems. Thus, unlike LWD, this method of pressure monitoring does not entail any additional expense for data gathering.

An extensive list of drilling parameters is given in Figure 3.

Taken in isolation, much of this data is inconclusive. For example, a change in rate of penetration can indicate that a formation top has encountered, or possibly that the bit performance has deteriorated due to wear. However, when the ROP change is accompanied by other indicators, such as an increase in sand content and a change in chloride count, there is sufficient information to support a model update for a formation top. With a few exceptions all of the measures are indirect indicators of borehole conditions. Taken together, they form a robust set of information from which to build viable pressure estimations. Figure 4 illustrates how some of the drilling parameters correspond to factors important in determining pore pressure.

In practice, the process begins with a planning session between the pressure analyst and members of the drilling team as selected by the operator. Roles and responsibilities are firmly established, along with clear lines of communication, protocols for secure data transmission, and an agreement on what factors will trigger an update to the model. The information flows are shown in figure 5. Because the software is PC-based the analyst can be present at the rigsite with no loss of modeling capability. However, most operators elect to have the analyst work remotely to reduce cost.

The software system is optimized to consider only those factors relevant to pore pressure estimation. Unlike the more ponderous, intensive techniques like finite element analysis the model can be updated very quickly, typically within 15 minutes after new data is received. These rapid turnaround times, along with concise, straightforward reporting of the updated model findings are keys to getting actionable information into the hands of decision-makers.

In a typical application, real-time updates to the model are significant enough to change the mud weight recommendation 2-4 times during the course of drilling.

One lesson learned is that, to provide effective decision support, analysts must have a good understanding of rigsite operations. For example, in one case a change in background gas readings was found significant enough to revise the forward-looking pore pressure estimate. However, since the data was not supported by changes in other drilling parameters, the knowledge systems analyst recommended that the gas trap be checked for blockage before any action was taken. Mud buildup in the possum belly on the mud return line was revealed to be the source of the anomalous gas reading. This example demonstrates the strength of using a system which is not heavily dependent on any single parameter.

Performance in the absence of LWD data
In a typical instance, a major oil company was drilling a 14,000 foot well in the Gulf of Mexico with minimal offset well information. Concerned about possible well control and integrity problems, the drilling team commissioned a real time pore pressure model that relied upon LWD data to generate updates as warranted. About 1,800 ft above TD the sonic and resistivity tools malfunctioned. The team was faced with a tough choice: make a costly trip to replace the tools, or drill ahead with a higher risk of well control and integrity problems. They opted to drill ahead, while continuing to update the pore pressure model using well response and drilling data as inputs. This new updating methodology resulted in significant changes in the mud program which helped the well to be drilled to successfully to TD without any control or other pressure-related drilling problems.
Subsequently, when the well was logged with wireline, the log-derived pore pressures were very close to the values predicted using drilling data.

As with any analysis, the addition of other independent sources of information will improve results, provided the information is not erroneous. The consideration here is whether the improvement in model accuracy warrants the huge additional cost of LWD systems. One way to look at this issue is to consider the decrease in pore pressure estimation error as additional estimation capabilities are added. As is illustrated in figure 6, no estimation (e.g. using hydrostatic estimates only) could lead to mud weights being 5ppg or more too high or low at points within the well. With a pre-drill model, the error is typically reduced to a range of ±2-3ppg, at a cost of $50-$100K. Continuous model updating using drilling parameters can reduce uncertainty to ±1-1.5ppg, at a cost of $20-50K. With LWD data the error can be reduced to as low as 0.5ppg, but at a huge additional cost, often over $1M. If the safe operating window is +/-1.5ppg or greater then the running of LWD tools to further refine the estimate is simply overkill. The objective should be to select a methodology based on the adequacy, not accuracy, of the estimate.

**Benefits of Proposed Solution**

The methodology described above employs principles that are common to all geologic basins. Accordingly, the solution is universally applicable, including the Ultra HTHP applications being anticipated. It also allows the same model to be used for multiple wells in the same field, reducing the overall cost of modeling while improving the accuracy. Also new well locations can be integrated into the existing model in a short time.

By design, the models are inexpensive to build. They can be updated rapidly, in a matter of minutes, without any requirements for additional data. The biggest advantage is that improved pore pressure estimation improves safety during the most challenging phases of drilling, and can be used to reduce drilling problems related to formation integrity throughout the Wellbore.

If this successful trend continues, pore pressure modeling will become accessible, both economically and operationally, to a wider selection of drilling projects.

**Conclusion**

Forward modeling of wellbore pore pressures is becoming established as a cost-effective method to reduce the incidence of pressure-related drilling problems. Some regulatory bodies are recommending the process as a best practice in high-risk wells, such as HTHP applications. Although the modeling process currently uses LWD and wireline data extensively, acceptable results can be obtained through the use of other available information. This may be important for UHTHP wells, where log data may be difficult or impossible to obtain due to tool limitations.

**Acknowledgments**

**Nomenclature**

*Define symbols used in the text here unless they are explained in the body of the text. Use units where appropriate.*

- **LWD** = logging-While-Drilling
- **TD** = Total Depth
- **ROP** = rate of penetration

**References**


Figures

![Pie chart showing categories of safety aspects for HPHT wells](image)

Figure 1 The U.K. Health & Safety Executive Report on HTHP wells 2005, cited that for HTHP exploratory or appraisal wells, prediction of the pore pressures in the prospective zone should be a key element in well design.
Figure 2  Without LWD or wireline log inputs, pore pressure estimates must rely on the pre-well planning model updated with drilling data alone. This may increase the error in the pore pressure estimate, but not outside acceptable limits.
Mud Logs—ROP (Inst/Avg), Total Hydrocarbons (Units/%), Chromat Breakdown (C1, C2, C3, IC/NC4, IC/NC5), Hydrocarbon Indicator, Porosity (basic), Show Qualifiers (basic), Cut/Stain/Fluorescence, Percent Lithology, Interpretive Lithology (sometimes), Lithology Descriptions, Rock Type (shale, sandstone, siltstone, carbonates, evaporites, coal, conglomerate, etc.), Index Minerals (pyrite, Glauconite, 2ndary calcite/aragonite, Micas), Basement Definitions and rock type(s), fossils (basic species identification)

Drilling Fluid Reports—Mud Type, mud weight, gas cut/water cut, chlorides, PV/YP, API WL, HTHP WL, pH, Ions (calcium, Potassium, chlorides, KCl, NaCl, Others): These should supersede log header as the principal source of mud weight data.

Engineering Mud Logs—Rock Densities (Shale Density or Shale Bulk Density), Relative Flow Out (absolute sometime), trip properties (abnormal fill, torque/drag, bridging, reaming, fill on bottom, trip gas, Swab-Surge), connection gas, trip gas (short trip gas, dummy trip gas), well flow (SIDPP/CASP), lost circulation (MW/Depth), ECD (supercedes MW).

Engineering Morning Reports—Compilations or syntheses of all wellsite daily reports; basic overview of daily wellsite operations; a ready source of basic data.

Drill Bit Reports—Can derive formation abrasivity indices from individual bit run data and determine suitability of bit run for derivation of pseudo-drilling exponent type variables.

Pressure Tests: Leak-Off Tests (LOT), Formation Integrity (FIT) and Pressure Integrity Tests (PIT), EMW or PSI values (important to distinguish between full LOT and FIT/PIT).

Mud Logging Data
The mud logging information may provide the only detailed record of the actual geology and lithology drilled. Generally presented as percent lithologies, occasionally as an interpretive log, may include written sample descriptions. The following are the primary information of use to the pressure analyst that originates with the mud logger:

- D-exp or Dcs – uncorrected drilling exponent, or corrected for mud weight or ECD effect (should plot both to help visualize amount of over-under balance)
- ROP (rate of penetration in feet per hour and/or minutes per foot
- WOB weight on bit
- RPM rotary table revolutions per minute
- Mud Weight in/out
- Mud temperature in/out
- Drill gas (Total and/or Compensated for ROP and hole volume)
- Connection (CG), trip (TG), short-trip (STG), dummy trip (DTG) gas levels
- Gas Chromatography (C1, C2, C3, IC4/NC4 and IC5/NC5)
- Equivalent Circulating Density (ECD)
- Torque
- CEC or cation exchange capacity
- Hydrocarbon Show intervals
- Bit Records with ROP performance
- General mud properties
- Continuous Chlorides in/out plots
- Well control pressures from Shut-in events (shut in drill pipe and casing pressures)
- Density Log whether Bulk Density or “sink or swim” measurement technique; differentiate between “bulk scale” density (preferred) or “sink and swim (too subjective; lots of operator error; requires experience)
- Relative (%) flow out or absolute flow measurement (such as Foxboro magnetic flow meters, sonic or Doppler devices)

Figure 3 Extensive list of drilling parameters useful for pore pressure prediction. Source: Best Practice Procedures for Predicting Pre-Drill Geopressures in Deep Water Gulf of Mexico, Knowledge Systems Inc., June 2001
Figure 4 Correlation of selected drilling parameters to geopressure parameters used in building the geomechanical model
Figure 5 In a real-time pressure modeling system, the pressure analyst monitors drilling parameters provided by the rig. New information is input to the pressure model, and the revised pressure prediction is provided to the operator with an explanation of significant changes. In this example, recommendations were provided to the drilling engineer, who used the model as input into the well decision-making process.
Figure 6 Illustrative cost-benefit diagram of various pore pressure estimation methodologies. The vertical scale is relative cost (not to scale). The horizontal axis is estimation error.