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Plan for Success: Review of Deepwater Well Planning & Execution

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Abstract
Deepwater operations are inherently expensive, but thorough and comprehensive pre-well planning can aid in reducing drilling costs. Information from computer modeling of casing, drill string and bit design is invaluable for making informed decisions that can effect the success of the drilling operation. Important design considerations for reducing drilling costs are maximizing rates-of-penetration (ROP), minimizing equivalent circulating densities (ECD's) and optimizing pressure losses in the circulating system. The well planner analyzes various combinations of ROP, flow rate and drilling fluid properties with each casing, drill string and bit configuration. This is a very time-consuming and data intensive process, the accuracy of which is influenced by the computer model and analysis techniques used.

This paper reviews the use of engineering software for well planning and drilling operations. Information is presented from two deepwater wells drilled in the Gulf of Mexico. New analysis techniques were developed specifically for well planning in these types of wells. Innovative communications technology allows simulations created onshore in the planning phase to be transferred offshore for use in the execution phase.

Introduction
The significant technical challenges of drilling in deepwater are complicated by the sensitivity of the preferred drilling fluid to the drilling environment. Synthetic-based muds (SBM) are the fluid-of-choice for deepwater operations because they consistently allow operators to realize significant reductions in overall well costs. These savings result from reductions in bit trips, improved borehole stability, increased rates of penetration and, in some cases, the elimination of casing strings.

Despite their considerable technical merits, synthetic-based drilling muds are not always trouble-free. The occurrence of lost circulation when using SBM is a major concern for deepwater operators. Excessive losses of mud volume can temporarily shut down drilling operations and add a tremendous expense to overall well cost.

Modern computer technology has enabled the design sophisticated hydraulics models for engineering applications. Hydraulics and hole cleaning models are extremely important for ensuring success when drilling complex wells. Deepwater and high temperature/high pressure (HT-HP) wells are particularly challenging and pre-well modeling can be an enormous asset towards project success.

Modeling Considerations
Drilling hydraulics are analyzed at actual downhole conditions, whether in deepwater where circulating temperatures are typically below 200° F or in high temperature/high pressure wells, where temperatures may exceed 400° F. Temperature and pressure effect both the rheology and density of drilling fluids, particularly invert-emulsion drilling fluids. These parameters are corrected for local conditions before an overall integrated prediction of downhole pressures is performed.

Important modeling considerations have been identified for deepwater and HT-HP wells and, because their importance cannot be over-emphasized, they will be reviewed in this paper. These critical considerations are:[1,2,3]

- temperature model,
- HT-HP rheological model,
- density model,
- compositional model,
- finite-difference analysis (hydraulic grids)
- hole cleaning analysis and
- swab/surge analysis

Temperature Model
Predicting annular temperatures is not a trivial task and thermal conditions inherent to deepwater wells add to the challenge. These wells exhibit dual gradients: a negative gradient exists from surface to the mud line (water column), followed by a positive gradient below the mud line. When initiating circulation after periods of static conditions, the annular temperature profile changes after the volume of mud exposed to the cold water column opposite the riser is incorporated into the circulating system.

Another condition unique to deepwater arises from boosting the riser. Here, cooler mud from surface continually enters the riser and alters the circulating temperature profile within the mud column. Variations in the frequency and rate at which boosting occur complicates predictions of circulating temperature and pressure profiles. Other examples include drilling operations characterized by multiple gradients such as drilling through salt domes. Deepwater wells drilled through a salt dome can have four temperature gradients.

Temperature models fall into two categories, either steady state or dynamic. Most programs use a steady state model. A detailed discussion on temperature models is beyond the scope of this paper, although some important variables merit mention. These include heat capacity and heat transfer coefficients of the formation and drilling fluid, geothermal gradients, mass flow rate and the viscosity and density of the drilling fluid.

Modern hydraulics models characterize downhole temperatures by direct calculation, or by allowing the user to define a temperature profile. Steady-state models calculate the profile after extended periods (steady state), such as when geothermal equilibrium is reached and annular temperatures have stabilized. Dynamic models simulate changes in downhole temperature and pressures as a function of time. Regardless of the type of temperature model used, an accurate temperature profile is the single most important parameter for accurate analysis of downhole pressure.

The temperature model used in this paper calculates downhole temperature profiles based on the conservation of energy within a control fluid volume. This is done within the drill string, annulus and the formation.[4]

The equation for conservation of energy for a control volume inside the string is:

$$\pi\, d_p U_p \left(T_a - T_p\right) = m c_p \frac{\partial T_p}{\partial z} + \rho\, c_p A_p \frac{\partial T_p}{\partial t}$$

Inside the annulus,

$$\pi\, d_a U_a \left(T_f - T_a\right) - \pi\, d_p U_p \left(T_a - T_p\right) =$$

$$- m c_p \frac{\partial T_a}{\partial z} + \rho\, c_p A_a \frac{\partial T_a}{\partial t}$$

And inside the formation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T_f}{\partial r}\right) + \frac{\partial^2 T_f}{\partial z^2} = \frac{\rho_f c_{pf}}{k_f} \frac{\partial T_f}{\partial t}$$

Initial and boundary conditions are required to solve these equations.

HT-HP Rheological Model

The rheological properties of SBM change under downhole conditions. Bottom-hole pressures on deepwater wells can approach 20,000 psi, and mud line temperatures in the Gulf of Mexico can be as low as 35° F. A HT-HP viscometer such as the Fann® Model 70/75 measures downhole rheological properties under these conditions. The accuracy of rheological modeling improves with greater numbers of pressure and temperature combinations. Ideally, these combinations should mirror actual annular conditions to facilitate interpolation between data points and minimize errors. Input data should cover the whole of the 2-dimensional space defined by the range of pressure and temperature to avoid partial extrapolation. Extrapolating data outside of the range of the HT-HP rheology matrix increases error.

Shear viscosity is calculated at each dial reading using 3-dimensional interpolation. A bi-cubic spline method is used when a square matrix of HT-HP temperature and pressure data is available. In the case of fewer readings, pre-defined equations embedded in the program surface-fit Fann 70 dial readings as a function of pressure and temperature.

Density Model

The model corrects the density of the base fluid by calculating the change in density as a function of local pressure and temperature. The compressibility of a base fluid at a known temperature follows this general equation:

$$Compressibility = -\frac{\frac{\Delta V}{V}}{\Delta P}$$

Equations derived from pressure-volume-temperature (PVT) data calculate density as a function of temperature and pressure. Figures 1-2 show the dependency of density with pressure and temperature of a typical SBM base fluid.[1]

Compositional Model

A compositional model calculates mud density using PVT characteristics of the liquid fraction. Due to the compressible nature of base fluids, an accurate reference temperature and pressure (usually atmospheric) for initial mud density is required.

Each base fluid has a characteristic equation to define PVT behavior. The finished mud is described as the composition of various liquid and solid fractions, expressed as the percentage of each component. The following equation calculates the local density by considering the individual changes in density of each fluid component.[5,6]

$$\rho\,(p,T) = \frac{\sum_{i=1}^{n} \rho_i\ f_i + \sum_{j=1}^{m} \rho_j\ f_j}{1 + \sum_{i=1}^{n}\left(\frac{\rho_i}{\rho_{ix}} - 1\right)}$$

The subscript "i" indicates the "n" liquid components, while "j" indicates the solid components. The index "x" indicates the density of fluid "i" at local pressure and temperature.

Finite-Difference Analysis (Hydraulic Grids)
The benefits of calculating temperature, density and rheological properties under downhole conditions are lost unless these properties are continually updated throughout the wellbore. This requires the wellbore to be divided in grids or segments to allow for finite-difference mathematical analysis of these parameters under local conditions.

The accuracy of these calculations improves when the maximum grid length is less than 100 feet. Changes in the drilling assembly, well bore geometry or survey further reduces the grid length. Downhole properties such as rheology and density are calculated within each grid and used as initial conditions in the next grid. A finite-difference technique is used for hydraulics analysis in these segments, and numerical integration is used to calculate cumulative pressures.

Calculations for temperature, pressure, rheology and pressure loss are performed at each grid, but are populated from different sources. This is done because some analysis parameters are independent, while others are inter-related. The temperature in each grid is not dependent of other grids and, therefore, it is taken directly from the temperature profile. On the other hand, pressure, rheology and local density are inter-related and dependent upon previous grids. Numerical integration techniques are required to calculate the cumulative effects of these properties. The local density of the SBM in each grid is calculated using temperature and pressure conditions within that grid, whereas the equivalent static density (ESD) is the cumulative hydrostatic pressure acting from all grids. Temperature and pressure updates in a hydraulic segment are shown in Figure 1.

The following section illustrates the iterative solution procedure required to update parameters within each hydraulic segment. The calculation of ESD uses the following equation:

$$ESD_i = \frac{p_{static\,i}}{g\ TVD_i}$$

The static pressure is calculated with the equation

$$d\,p = \rho\left(p,T\right) g\ dz$$

Due to the dependency of the density on the pressure, the equation is solved iteratively.

$$p_{i+1} = \rho\left(p_i\ ,T\right) g\,\Delta TVD_{i+1}$$

The ECD calculation considers the generalized frictional pressure losses (dpf) when calculating the circulating pressure.

$$ECD_i = \frac{p_{circulating\ i}}{g\ TVD_i}$$

The circulating pressure is calculated using equation:

$$d\,p = \rho\left(p,T\right) g\ dz + dp_f\left(\rho\left(p,T\right),\mathrm{Re}\right)dx$$

Iterative techniques are used when solving this equation because of the dependency of density on pressure.

$$p_{i+1} = \rho\left(p_i\ ,T\right) g\,\Delta TVD_{i+1} + dp_f\left(\rho\left(p_i,T\right),\mathrm{Re}_i\right)\Delta MD_i$$

dp_f represents the frictional pressure loss equation.

Hole Cleaning Analysis
An important economic benefit that operators realize from the use of SMB in deepwater is high rates-of-penetration. Typically, operators wish to drill out of 20" casing with a 17 ½" bit using SBM. The combination of large hole diameters and high rates-of-penetration can potentially lead to disaster due to high volumes and rates that cuttings are generated. At risk in these situations are gains made towards ECD management and reducing lost circulation.

Hole cleaning analysis is a critical technology for annular pressure management in deepwater wells. This analysis predicts and optimizes flow rates needed for hole cleaning. It also calculates concentrations of transported cuttings and bed heights within each grid. The hole cleaning model is based on the balance of forces acting on cuttings in the annulus.[7] Three modes of cutting movement are distinguished:

- Settling - Cuttings move downwards due to the gravitational force acting against buoyancy and the drag force.
- Lifting - A cyclic motion of moving cuttings in the area of high fluid velocity due to lift and buoyancy forces, followed by settling.
- Rolling - Cuttings roll on the lower side of the annulus when lift and drag forces exceed gravitational and plastic forces.

This model provides the drilling engineer with a useful tool for identifying areas in the wellbore where problems related to hole cleaning may occur. Input parameters include cutting size and density, mud weight and rheology, ROP, survey, drill string, wellbore geometry and flow rate. The model uses a force balance analysis within each grid and identifies the most difficult grid for hole cleaning. Examples include the riser (settling mechanism), the build section (lifting mechanism) and the lateral or horizontal section (rolling mechanism).

Well Planning Phase
An important goal of the pre-well planning process is to balance the economic benefits derived from the use of SBM against the technical challenges found in deepwater. The role of the drilling fluids provider in the well planning process has evolved such that the provision of hydraulics analyses has become a basic service. Generally, the well planner establishes the potential for lost circulation arising

from use of SBM in this narrow pressure environment by comparing predicted ECD to the pressure gradient. Other equally important parameters evaluated during well planning include:

- mud property optimization,
- casing string design,
- drill string design,
- bit design,
- survey,
- surface limitations (SPP and mud pumps),
- ROP optimization,
- hole cleaning analysis and
- swab/surge analysis

These parameters can be evaluated independently; however, they rarely act in isolation during the drilling process. For example, ECD is influenced by flow rate, mud properties, rate-of-penetration and annular cuttings load. Similarly mud properties, flow rate, bit nozzles, and drill string designs are some of the variables effecting surface pressures. The engineering software presented in this paper is part of the Advantage SM System, an enterprise database system for well planning, well site reporting and engineering analysis. This is a modular platform and can be used stand-alone or networked among integrated services such as drilling fluids, surface logging, MWD, pressure/dynamics, drilling systems and directional drilling.

During pre-well planning, the well planner collected a detailed list of contractor-supplied equipment prior to designing drilling assemblies for each section. This list included mud pumps and liner sizes, rated working pressures on liners, allowable working pressures for each liner and tubular specifications. The operator provided expected pore pressure and ROP information. The proposed SBM was tested extensively, including Fann 70 rheological testing, and the collective drilling fluid and operational information was combined and used to predict:

- maximum standpipe pressure,
- bit TFA,
- minimum surface mud weight,
- annular, drill string and bit pressure losses,
- ECD at various combinations of flow rate and ROP,
- flow rates required for hole cleaning, and
- intervention techniques for hole cleaning,

Planning considerations for Wells A & B are presented in Table 1. The well planner designed the hydraulic system using 5.5” drill pipe and a rig-imposed surface pressure limitation of 4200 psi. The expected fracture pressure at casing point was 10.9 and 12.5 lbm/gal equivalent mud weight for the 17” and 12-¼” sections, respectively. Hydraulics and hole cleaning were modeled at ROP of 100 and 150 feet/hour.

A pre-well analysis of the proposed 17” section of Well A appears in Figure 4. The top portion of the figure is a spreadsheet, based on HT-HP analysis, detailing pressure losses within the circulating system. This spreadsheet and the accompanying graphic were developed specifically for comprehensive HT-HP analysis of pressure losses, bit hydraulics and hole cleaning efficiency during well planning. The user defines an operating flow rate and a decrement of flow rate. Afterwards, the hydraulics parameters are calculated, tabulated and presented graphically at 10 decrements of flow rate. For example, the operating flow rate in Figure 4 is 1050 US gallons/minute and the decrement of flow rate is 25 US gals/min. These parameters were calculated and graphed over this range of flow rates. Calculated data includes standpipe pressure, ECD at bit and casing shoe, drill string, bit and annular pressure losses, impact force, hydraulic horsepower and jet velocity. The program also calculates the bit TFA required to maximize SPP at each flow rate, with accompanying bit hydraulics.

The information presented in Figure 4 was based on an average ROP of 100 feet/hour. This data, compared to the information in Table 1, indicates that surface and fracture pressure limitations are not exceeded at a maximum flow rate of 1050 US gals/min. Using a bit TFA of 1.7 inch^2, the SPP and ECD (at casing shoe) are 4121 psi and 10.64 lbm/gal, respectively. The bit TFA would have to be reduced to 1.5227 inch^2 to maximize SPP when operating at 1050 US gals/min.

Figure 5 presents similar information based on modeling performed in the 12-¼” section of Well A at an average ROP of 100 feet/hour. The expected surface mud weight at total depth in the 12 ¼” section was 11.9 lbm/gal. Hydraulic analyses of the circulating system were modeled at flow rates ranging from 850 to 625 US gals/min without exceeding surface and casing shoe pressure limitations.

The drilling engineering requested modeling at higher flow rates in the 17” section of Well B. An initial flow rate of 1200 US gals/min and decrements of 50 US gal/min were modeled for this well using a surface mud weight of 10.4 lbm/gal. Changes were made to the proposed drill string, including motors and MWD, resulting in higher drill string pressure losses compared to Well A. Consequently, surface pressure ratings were exceeded at flow rates above 900 US gals/min (Figure 6). An average ROP of 150 feet/hour was used in the 17” section of Well B.

The 12 ¼” section of Well B was modeled at an average ROP of 150 feet/hour and with an expected mud weight at total depth of 11.6 lbm/gal. The maximum flow rate expected in the section was 850 US gals/min. Modeling results presented in Figure 7 indicate that surface and annular pressures at these flow rates would not exceed the constraints from Table 2. However, the graphical portion of Figure 7 indicates that a minimum flow rate of 750 US gals/min is required for hole cleaning in this section.

The drilling engineer used this information in final planning of well design. This information was also used for determining if additional equipment, such as larger drill pipe, circulating subs or downhole tools was needed to drill these wells.

Case Transfer Mechanism

Information and data in the computer model is stored in local or networked databases in the form of an engineering case. An innovative communications technology, the case transfer mechanism, provides the user with access to data sets stored in the data tables. This function allows the user to import and edit actual data or input hypothetical data and then use it to create "what if" scenarios. One can then save this special-use data as an engineering case.

Case transfer technology deals primarily with Microsoft® data shaping, a hybrid of SQL. This allows the user to create hierarchical data by querying all related engineering data using header information from a selected ODBC-connected database. Database transactions use Microsoft's ADO data access layer. Case data is persisted into a standard format known as XML, or extendable mark up language. The XML format consists of two parts; 1) the XML schema, which describes the position of the data in the file and 2) the data as it appears in the database.

A benefit of using XML as the file format is the ease in which data may be migrated into third party applications and transmitted through the 80 port. Microsoft ADO has the native ability to read an XML file directly, which allows the user to create a connection to a SQL server database and load the engineering case. With this process, the data remains in a pure form from export to import, which decreases the possibility of corruption during transfer.

Multiple onshore & offshore users share engineering cases using electronic mail, a network or through the Internet. Floppy disks or CD-ROM are used to transport cases when electronic transfer is unavailable. This process eliminates duplication of efforts and ensures accuracy and efficiency of knowledge transfer.

Drilling Phase

Hydraulics analyses performed during well planning were based on expected conditions and contained many unknowns. The drilling process is very dynamic and rarely do planned conditions mirror reality. Since the circulating system is an integral part of this process, there is tremendous value in performing hydraulics analyses under actual conditions. With this in mind, dedicated hydraulic engineers worked with the mud engineer and pressure tool provider during the drilling phase. Hydraulics modeling conducted at the rig site after displacing to SBM showed good correlation in ECD when compared to the INTEQ DCP pressure tool (Figures 8 & 10). Predicted ECD's were consistently were within 0.1 lbm/gal of the DCP pressure tool value. Poor correlation between predicted and acutal ECD occurred initially in some hole intervals because annular temperature profiles were not well defined. Modeling errors decreased with better definition of the annular temperature profile.

After establishing correlation between predicted and actual annular pressures, the engineer forecast trends, or "look ahead" scenarios, 300 feet in advance of the bit. This information was used to predict pressures and hole cleaning efficiency at casing points. It was also useful when making decisions concerning tripping when tools failed, timing of sweeps for hole cleaning intervention and calculating ESD before tripping pipe. In addition, the engineer compared predicted and actual surface pressures (Figure 9 and 11).

Hole cleaning modeling was routinely conducted at the rig-site using actual ROP and flow rates. The hole cleaning models alerted drilling personnel to potential hole cleaning problems and the timing of intervention techniques, such as sweeps. Swab and surge modeling was conducted on all bit trips, short trips, casing and liner runs. This information was communicated to the operator representative for determining trip speeds.

Samples of the SBM were sent to the laboratory on a weekly basis for routine mud checks and Fann 70 analysis. Laboratory results were used to update engineering cases with the most recent properties of the mud system, and were then transferred offshore via electronic mail. This continual stream of updated information, via the case transfer mechanism, facilitated the accuracy of hydraulics, hole cleaning and swab/surge modeling.

Conclusions

- The effects of annular temperature and pressures on SBM rheology and density must be considered for accurate pressure and hole cleaning predictions.
- Engineering software is available for comprehensive analysis of the circulating system during well planning and execution.
- Information collected during well planning is useful for making informed decisions in well design.
- Innovative communications technology facilitates sharing of engineering cases among an unlimited number of onshore and offshore users.
- ECD's calculated at the well site are typically within 0.1 lb/gal of measured values.
- Accuracy in ECD predictions at the well site is beneficial in maximizing operating time in case of tool failure.

Nomenclature

ECD = Equivalent circulation density
ESD = Equivalent static density
ROP = Rate of penetration
SPP = Standpipe pressure
TVD = True vertical depth
MD = Measured depth
DCP = Drill Collar Pressure tool

OD = Outside diameter
ID = Internal Diameter
BHA = Bottom-hole assembly
TFA = Total fluid area
GPM = flowrate, gallons per minute
d = diameter
dp_f *= Generalized frictional pressure*
psi = Pressure, pounds per square inch
lbm/gal = Mud weight, pounds of mass/gallon
f = Volume fraction of the fluid
Cp = Heat capacity
k = Heat conductivity
p = Pressure
r = Radial distance
Re = Reynolds number
ρ *= density*
t = Time
T *= Temperature*
g = Acceleration due to gravity
U = Heat transfer coefficient
Indices *(unless otherwise stated)*
a =-annulus
p= string
f = formation
I = index referencing a node in the FD grid

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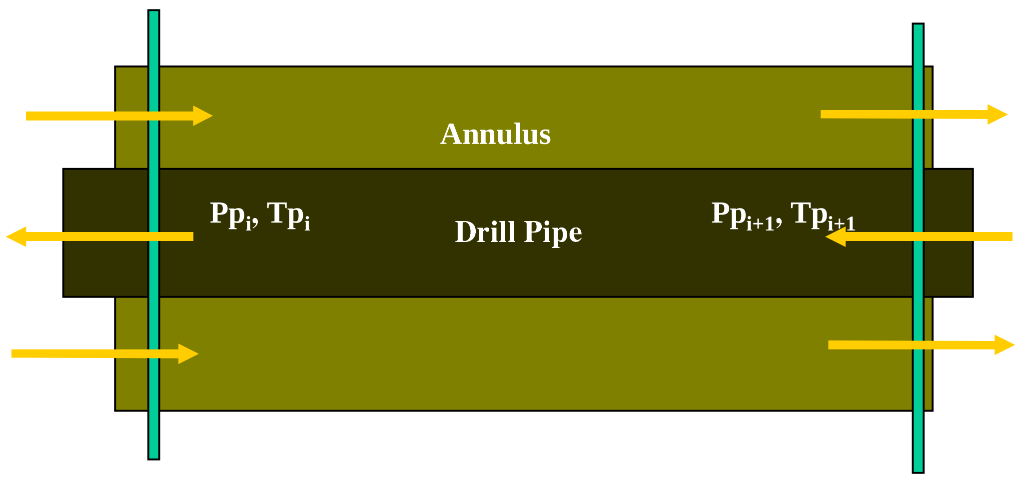
Table 1 – Planning Considerations Wells A & B			
17" Section		12 ¼" Section	
Water Depth	5685 feet	Water Depth	5685 feet
Fracture pressure	10.9 lbm/gal	Fracture pressure	12.5 lbm/gal
Max SPP	4200 psi	Max SPP	4200 psi
Drill Pipe OD	5.5"	Drill Pipe OD	5.5"
Rate-of-penetration	100 and 150 feet/hour	Rate-of-penetration	100 and 150 feet/hour



$$Ta = (Ta_i + Ta_{i+1}) / 2$$

$$Tp = (Tp_i + Tp_{i+1}) / 2$$

$$Pa = (Pa_i + Pa_{i+1}) / 2$$

$$Pp = (Pp_i + Pp_{i+1}) / 2$$

Figure 1. Temperature and pressure updates within hydraulic segments

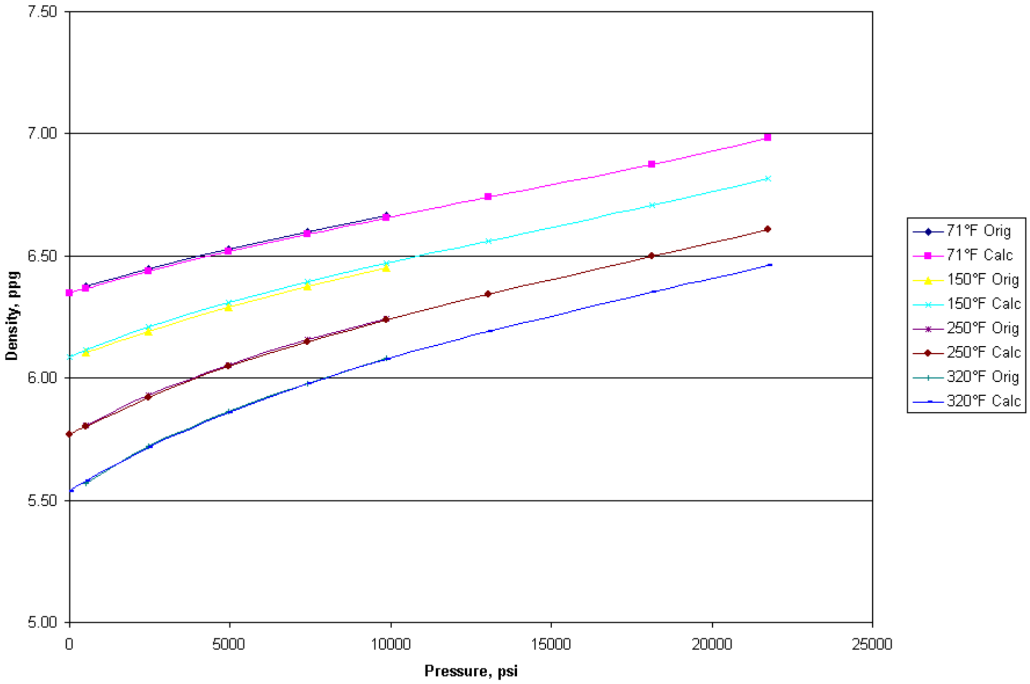


Figure 2. PVT on synthetic base fluid (Isobar)

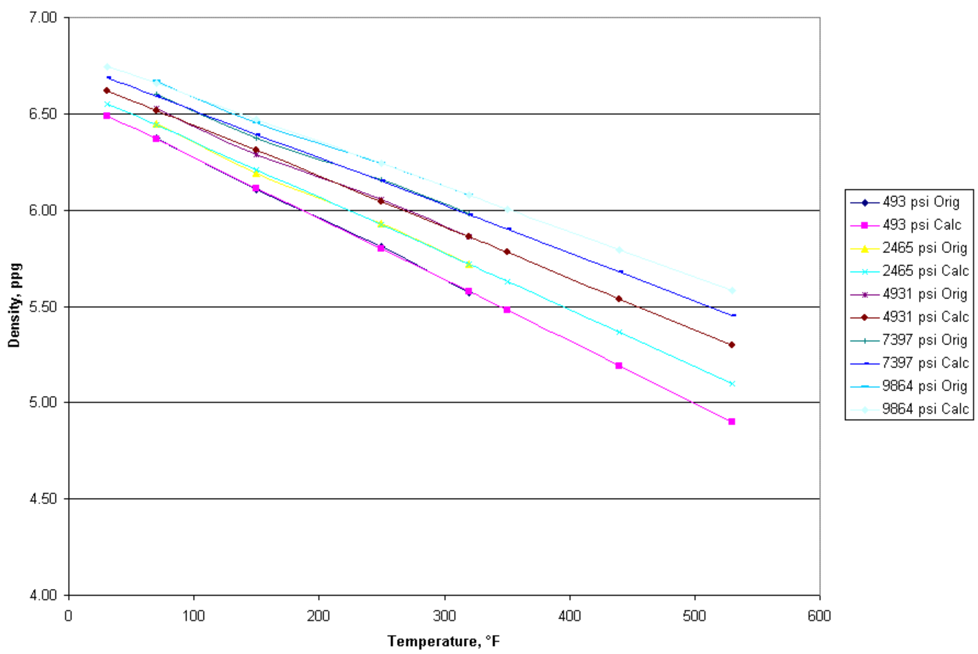


Figure 3. PVT on synthetic base fluid (Isotherm)

Drill String - String Volume 238.17 bbl | **Casing / Open Hole -** Hole Volume 3,822.56 bbl

Type	OD in	ID in	TJOD in	TJID in	Weight lb/ft	Length ft		OD in	ID in	Bottom MD ft
Drill pipe	5 1/2	4.778	7 3/8	4	26.33	10049	RiserBooster		19 3/4	5685
HWDP	5 1/2	4	7 1/4	4	56.19	690	Casing	20	18.376	8635
Jar	7	2.813				30	Openhole		17	11131
HWDP	5 1/2	3 5/16	7 1/4	3 7/16	58.10	180				
Sub - X/O	9 1/2	3	7 3/4	3 1/2		3				
Drill collar	9 1/2	3				60				
Stab - inline	9 1/2	3				6				
NM Drill collar	9 1/2	3				30				
Sub - circulation	9 1/2	3 1/2				8				
Stab - inline	9 1/2	3				6				
MWD / LWD - tool	9 1/2	2.810				30				
Sub - X/O	9 1/2	3				3				
Motor - steerable	9 5/8	6 1/8				31				
Sub - bit	9 1/2	3				3				
Bit - PDC - fixed cutter	17					2	**Annulus Volume**	3,484.25 bbl		

Flowrate	USgal/min	1050	1025	1000	975	950	925	900	875	850	825
Bit Hydraulics											
SPP	psi	4121	3951	3786	3625	3469	3317	3170	3026	2887	2752
Bit Pressure Drop	psi	322	306	292	277	263	249	236	223	211	198
%SPP	%	7.80	7.75	7.70	7.65	7.58	7.52	7.45	7.37	7.29	7.21
Jet Velocity	ft/sec	198.2	193.4	188.7	184.0	179.3	174.6	169.9	165.1	160.4	155.7
Impact Force	lbf/in^2	5.0	4.8	4.5	4.3	4.1	3.9	3.7	3.5	3.3	3.1
HSI	HP/in^2	0.88	0.82	0.76	0.70	0.65	0.60	0.55	0.51	0.47	0.43
TFA For Max SPP	in^2	1.5227	1.2626	1.0927	0.9696	0.8745	0.7978	0.7340	0.6794	0.6320	0.5900
Bit Pressure Drop	psi	401	555	706	852	994	1132	1267	1397	1523	1646
Jet Velocity	ft/sec	221.2	260.5	293.6	322.6	348.5	372.0	393.4	413.2	431.5	448.6
Impact Force	lbf/in^2	5.6	6.4	7.1	7.6	8.0	8.3	8.5	8.7	8.8	8.9
HSI	HP/in^2	1.10	1.48	1.84	2.17	2.46	2.73	2.97	3.19	3.38	3.54
System Pressure Loss											
Surf Equip	psi	90	86	82	78	74	70	67	63	60	57
DP, CSG, LNR, TBG	psi	1884	1800	1718	1638	1561	1486	1413	1342	1273	1207
HWDP/CSDP	psi	480	458	437	417	397	378	359	340	323	305
DC/CT	psi	143	137	131	124	119	113	107	102	96	91
MWD	psi	705	671	639	607	576	546	517	489	461	435
Motor/Turbine	psi	350	350	350	350	350	350	350	350	350	350
Additional Tools	psi	104	99	95	90	86	82	78	74	70	66
Annulus	psi	43	43	43	43	43	43	43	43	43	43
ECD - CSG Shoe	ppg	10.64	10.64	10.65	10.65	10.66	10.66	10.67	10.68	10.69	10.70
ECD - Bottomhole	ppg	10.67	10.68	10.68	10.69	10.69	10.70	10.71	10.72	10.72	10.73

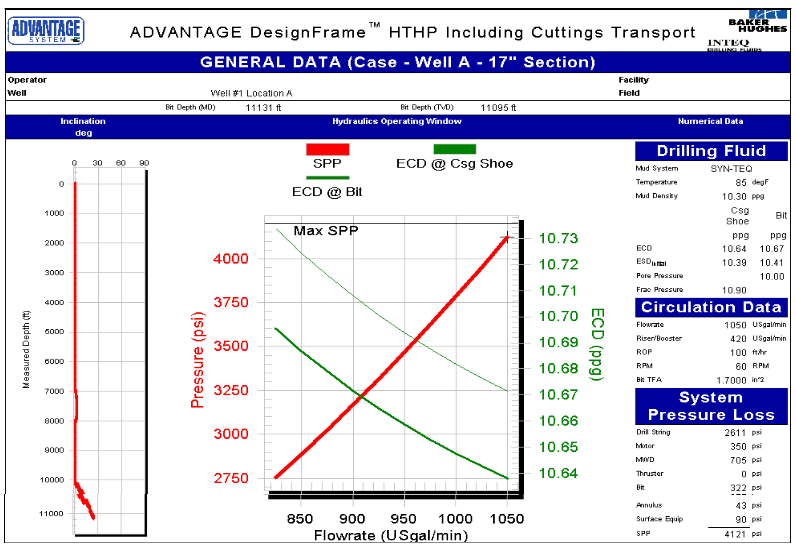


Figure 4. Pre-well analysis of Well A at 11,131' MD in 17" Section

Drill String - String Volume 299.84 bbl | **Casing / Open Hole -** Hole Volume 3,368.53 bbl

Type	OD in	ID in	TJOD in	TJID in	Weight lb/ft	Length ft		OD in	ID in	Bottom MD ft
Drill pipe	5 1/2	4.778	7 3/8	4	26.33	12826	RiserBooster		19 3/4	5685
HWDP	5 1/2	4	7 1/4	4	56.19	690	Casing	13 3/8	12.347	11131
Jar	7	2.813				30	Openhole		12 1/4	13929
HWDP	5 1/2	3 5/16	7 1/4	3 7/16	58.10	180				
Sub - X/O	8	3	7 3/4	3 1/2		3				
Drill collar	8	3				60				
Stab - inline	8	3				6				
NM Drill collar	8	3				30				
Sub - circulation	8	3 1/2				8				
Stab - inline	8	3				6				
MWD / LWD - tool	8	3 1/2				52				
Sub - X/O	8	3				3				
Motor - steerable	8	5 1/4				31				
Sub - bit	8	3				3				
Bit - PDC - fixed cutter	12 1/4					2	**Annulus Volume**	2,952.02 bbl		

Flowrate	USgal/min	850	825	800	775	750	725	700	675	650	625
Bit Hydraulics											
SPP	psi	4186	3988	3796	3609	3428	3251	3082	2916	2766	2628
Bit Pressure Drop	psi	755	711	669	628	588	549	512	476	442	409
%SPP	%	18.05	17.84	17.62	17.40	17.15	16.90	16.62	16.33	15.97	15.55
Jet Velocity	ft/sec	283.1	274.8	266.4	258.1	249.8	241.5	233.1	224.8	216.5	208.2
Impact Force	lbf/in^2	12.8	12.1	11.4	10.7	10.0	9.3	8.7	8.1	7.5	7.0
HSI	HP/in^2	3.22	2.95	2.69	2.44	2.21	2.00	1.80	1.61	1.44	1.28
TFA For Max SPP	in^2	0.9544	0.8455	0.7605	0.6913	0.6333	0.5833	0.5399	0.5010	0.4674	0.4375
Bit Pressure Drop	psi	770	923	1073	1219	1360	1498	1630	1760	1876	1981
Jet Velocity	ft/sec	285.7	313.0	337.5	359.7	379.9	398.7	416.0	432.2	446.2	458.3
Impact Force	lbf/in^2	13.0	13.8	14.4	14.9	15.2	15.4	15.5	15.6	15.5	15.3
HSI	HP/in^2	3.28	3.82	4.31	4.74	5.12	5.45	5.73	5.96	6.12	6.21
System Pressure Loss											
Surf Equip	psi	82	77	73	68	64	60	56	52	49	45
DP, CSG, LNR, TBG	psi	2104	1991	1881	1774	1670	1569	1470	1376	1285	1200
HWDP/CSDP	psi	322	306	290	275	261	246	233	218	209	202
DC/CT	psi	94	89	85	80	76	72	68	63	61	59
MWD	psi	182	171	161	151	141	132	123	114	106	98
Motor/Turbine	psi	500	500	500	500	500	500	500	500	500	500
Additional Tools	psi	68	65	62	58	55	52	49	46	44	43
Annulus	psi	79	77	76	74	73	71	70	70	70	71
ECD - CSG Shoe	ppg	12.23	12.24	12.24	12.24	12.24	12.25	12.25	12.26	12.26	12.27
ECD - Bottomhole	ppg	12.25	12.25	12.26	12.26	12.26	12.26	12.27	12.27	12.28	12.29

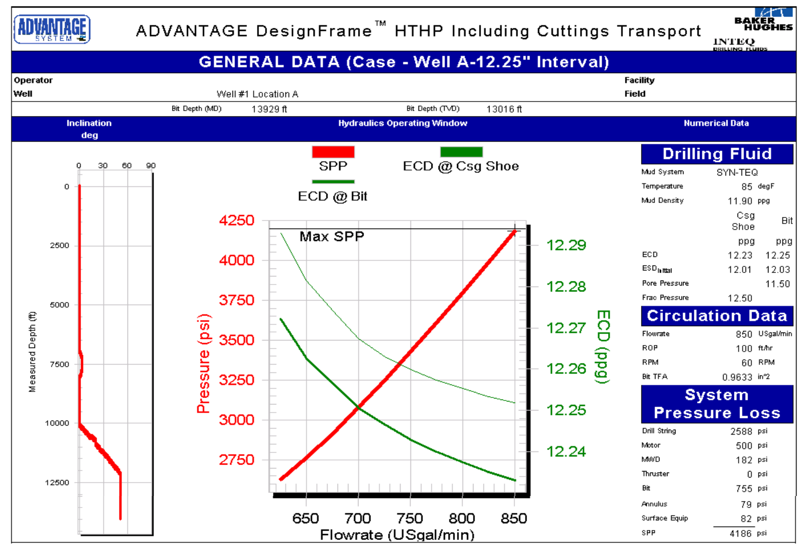


Figure 5. Pre-well analysis of Well A at 13,929' MD in 12 ¼" Section

Drill String - String Volume 229.66 bbl | **Casing / Open Hole** - Hole Volume 3,783.59 bbl

Type	OD in	ID in	TJOD in	TJID in	Weight lb/ft	Length ft		OD in	ID in	Bottom MD ft
Drill pipe	5 1/2	4.670	6 7/8	3	28.87	3180	RiserBooster		19 3/4	5679
Drill pipe	5 1/2	4.778	6 13/16	3	26.33	6777	Casing	20	18.376	8595
HWDP	5 1/2	3 1/4				475	Openhole		17	11000
Jar	6 3/4	3				32				
HWDP	5 1/2	3 1/4				300				
Sub - X/O	8	2.810				3				
Drill collar	8	2.810				90				
Sub - X/O	9 1/2	2.810				3				
Drill collar	9 1/2	3			217.00	30				
Stab - string	9 1/2	3				5				
MWD - pulser	9 1/2	3				58				
Sub - X/O	9 1/2	3				4				
Stab - inline	9 1/2	3				5				
Motor	9 1/2	7.600			144.17	36				
Bit - mill tooth - roller cone	17					2	**Annulus Volume**	3,448.48 bbl		

Flowrate	USgal/min	1200	1150	1100	1050	1000	950	900	850	800	750
Bit Hydraulics											
SPP	psi	6579	6119	5675	5247	4837	4445	4071	3716	3383	3069
Bit Pressure Drop	psi	423	389	356	324	294	265	238	212	188	165
%SPP	%	6.44	6.36	6.27	6.18	6.08	5.97	5.85	5.71	5.56	5.38
Jet Velocity	ft/sec	226.9	217.5	208.0	198.6	189.1	179.7	170.2	160.7	151.3	141.8
Impact Force	lbf/in^2	6.6	6.1	5.5	5.0	4.6	4.1	3.7	3.3	2.9	2.6
HSI	HP/in^2	1.32	1.17	1.02	0.89	0.77	0.66	0.56	0.47	0.39	0.32
TFA For Max SPP	in^2	0.0000	0.0000	0.0000	0.0000	0.0000	6.1124	1.3662	0.9370	0.7338	0.6059
Bit Pressure Drop	psi	0	0	0	0	0	20	367	696	1005	1296
Jet Velocity	ft/sec	0.0	0.0	0.0	0.0	0.0	49.9	211.4	291.0	349.8	397.1
Impact Force	lbf/in^2	0.0	0.0	0.0	0.0	0.0	1.1	4.6	6.0	6.8	7.2
HSI	HP/in^2	0.00	0.00	0.00	0.00	0.00	0.05	0.86	1.54	2.10	2.53
System Pressure Loss											
Surf Equip	psi	91	83	75	68	62	55	50	44	40	35
DP, CSG, LNR, TBG	psi	3233	2997	2765	2539	2320	2110	1907	1715	1534	1365
HWDP/CSDP	psi	966	888	815	745	679	617	558	503	451	402
DC/CT	psi	245	226	208	191	174	159	144	130	117	104
MWD	psi	925	849	777	708	642	579	520	464	411	361
Motor/Turbine	psi	550	550	550	550	550	550	550	550	550	550
Additional Tools	psi	91	84	77	71	65	59	53	48	43	39
Annulus	psi	54	53	52	52	51	50	50	49	49	48
ECD - CSG Shoe	ppg	10.91	10.92	10.92	10.93	10.94	10.95	10.95	10.97	10.98	10.99
ECD - Bottomhole	ppg	10.91	10.92	10.92	10.93	10.94	10.95	10.97	10.98	10.99	11.01

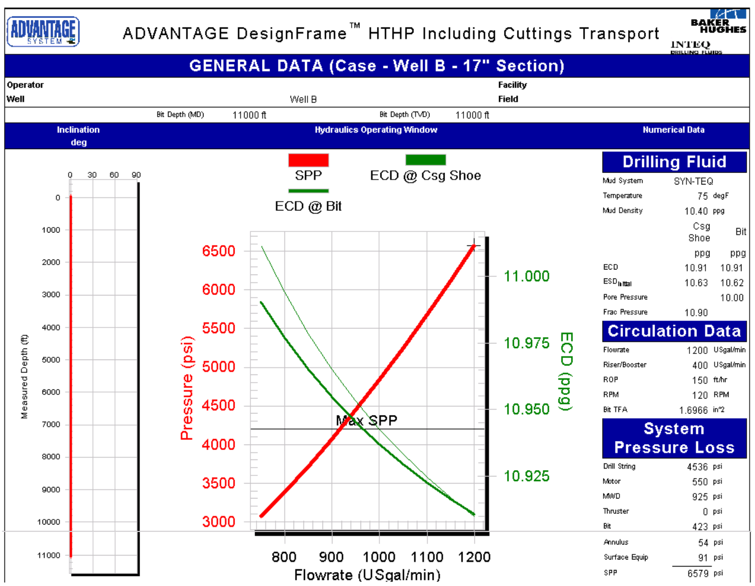


Figure 6. Pre-well analysis of Well B at 11,000'MD in 17" Section

Drill String - String Volume 278.00 bbl | **Casing / Open Hole** - Hole Volume 3,272.45 bbl

Type	OD in	ID in	TJOD in	TJID in	Weight lb/ft	Length ft		OD in	ID in	Bottom MD ft
Drill pipe	5 1/2	4.670			26.33	5570	RiserBooster		19 3/4	5685
Drill pipe	5 1/2	4.780	7 3/8	4	26.33	6777	Casing	13 3/8	12.347	11000
HWDP	5 1/2	3 1/4	7 1/4	4	56.19	450	Openhole		12 1/4	13272
Jar	6 3/4	3				32				
HWDP	5 1/2	3 1/2	7 1/4	3 7/16	58.10	300				
Sub - X/O	8	3.380	7 3/4	3 1/2		4				
NM Drill collar	8	2.810				30				
Stab - inline	8	2.810				5				
MWD / LWD - tool	8 1/4	2.810				58				
Sub - X/O	8	2.810				3				
Stab - inline	8	2.810				5				
Motor - steerable	8	2.810				36				
Bit - PDC - fixed cutter	12 1/4					2	**Annulus Volume**	2,877.05 bbl		

Flowrate	USgal/min	850	800	750	700	650	600	550	500	450	400
Bit Hydraulics											
SPP	psi	4187	3818	3471	3145	2854	2559	2287	2039	1813	1611
Bit Pressure Drop	psi	198	175	154	134	116	99	83	68	55	44
%SPP	%	4.73	4.59	4.44	4.27	4.06	3.86	3.62	3.36	3.05	2.71
Jet Velocity	ft/sec	147.0	138.4	129.7	121.1	112.4	103.8	95.1	86.5	77.8	69.2
Impact Force	lbf/in^2	6.5	5.7	5.0	4.4	3.8	3.2	2.7	2.2	1.8	1.4
HSI	HP/in^2	0.84	0.70	0.58	0.47	0.38	0.30	0.23	0.17	0.13	0.09
TFA For Max SPP	in^2	1.7944	1.0405	0.7748	0.6232	0.5222	0.4417	0.3779	0.3249	0.2793	0.2390
Bit Pressure Drop	psi	211	557	883	1189	1461	1740	1996	2230	2442	2633
Jet Velocity	ft/sec	152.0	246.7	310.6	360.4	399.4	435.8	467.0	493.8	516.9	536.9
Impact Force	lbf/in^2	6.7	10.2	12.1	13.1	13.5	13.6	13.3	12.8	12.0	11.1
HSI	HP/in^2	0.90	2.24	3.32	4.18	4.77	5.24	5.51	5.60	5.52	5.29
System Pressure Loss											
Surf Equip	psi	80	71	63	55	48	41	35	30	25	20
DP, CSG, LNR, TBG	psi	2066	1846	1638	1442	1264	1095	938	794	662	542
HWDP/CSDP	psi	526	475	428	382	345	294	247	205	166	132
DC/CT	psi	45	41	37	33	30	25	21	18	14	11
MWD	psi	462	409	360	313	270	230	193	160	129	102
Motor/Turbine	psi	675	675	675	675	675	675	675	675	675	675
Additional Tools	psi	57	52	47	42	38	32	27	22	18	14
Annulus	psi	77	74	71	69	68	67	67	67	68	70
ECD - CSG Shoe	ppg	11.92	11.92	11.92	11.93	11.94	11.96	11.98	12.00	12.04	12.09
ECD - Bottomhole	ppg	11.93	11.94	11.94	11.95	11.96	11.98	12.00	12.02	12.06	12.12

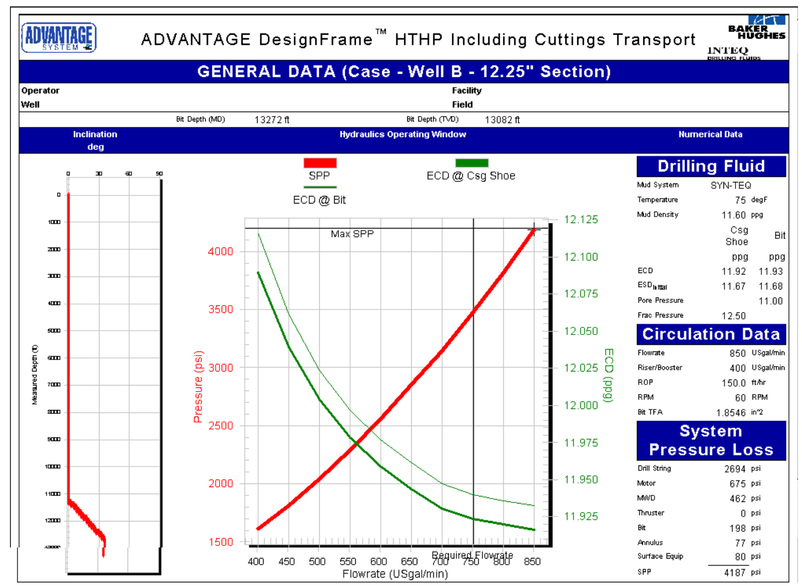


Figure 7. Pre-well analysis of Well B at 13,272' MD in 12 ¼" Section

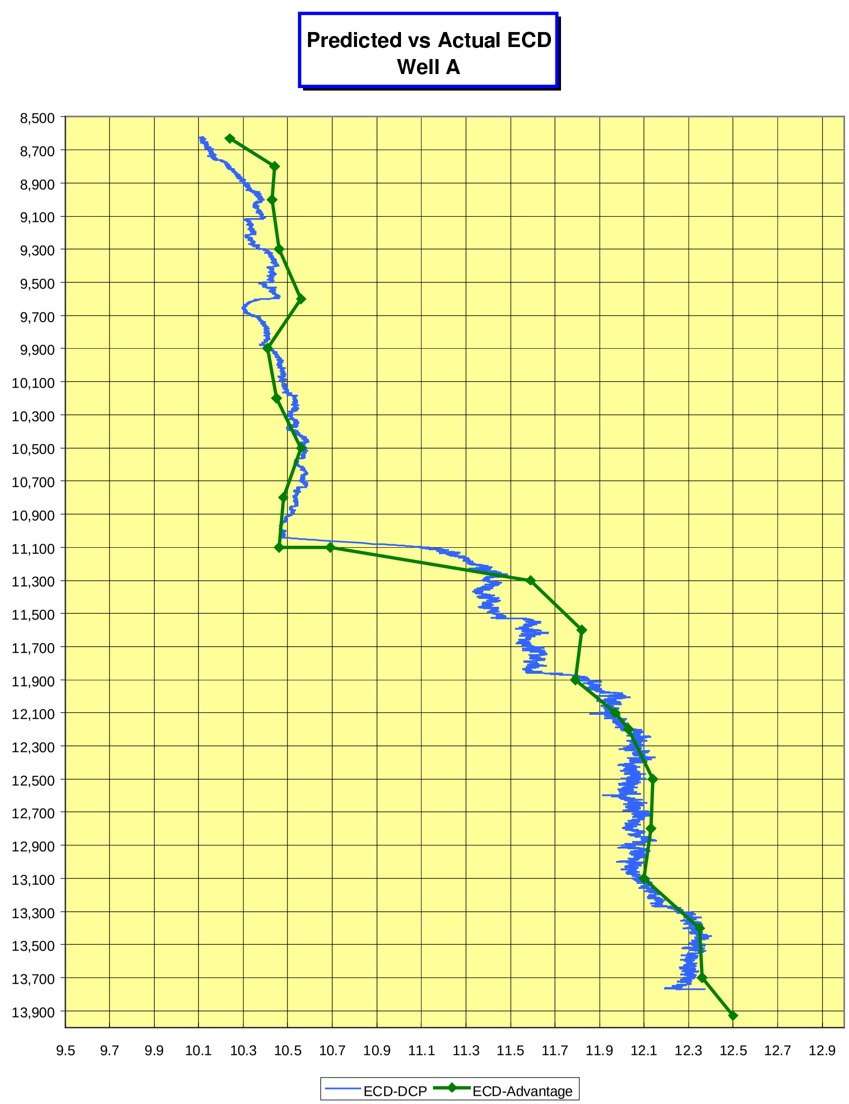


Figure 8. Actual vs Predicted Annular Pressure vs Depth – Well A

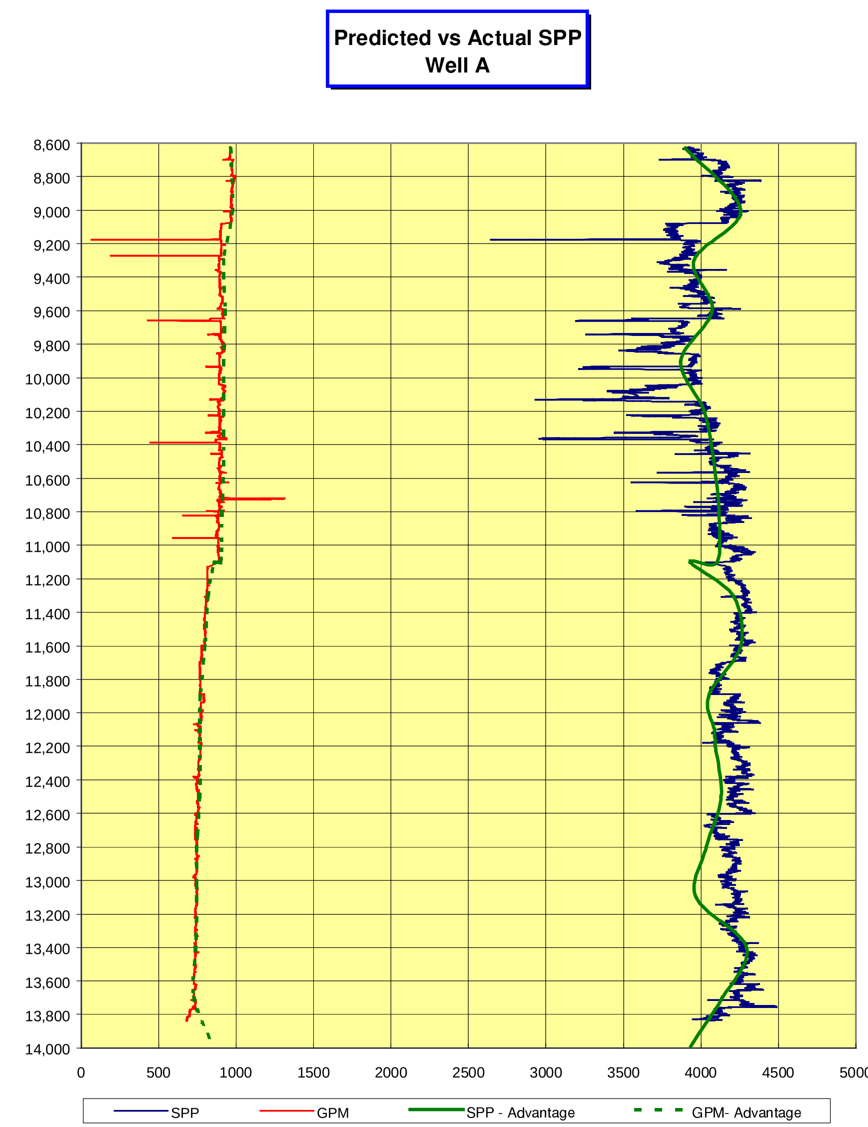


Figure 9. Actual vs Predicted Surface Pressure vs Depth – Well A

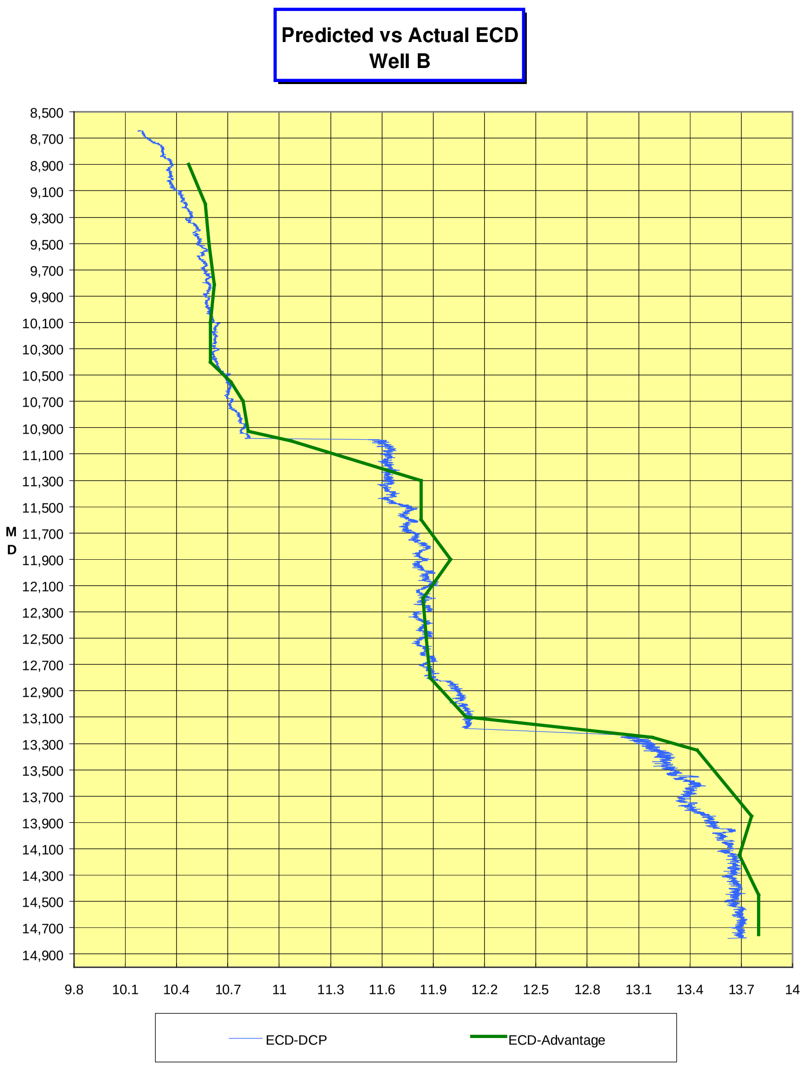


Figure 10. Actual vs Predicted Annular Pressure vs Depth – Well B

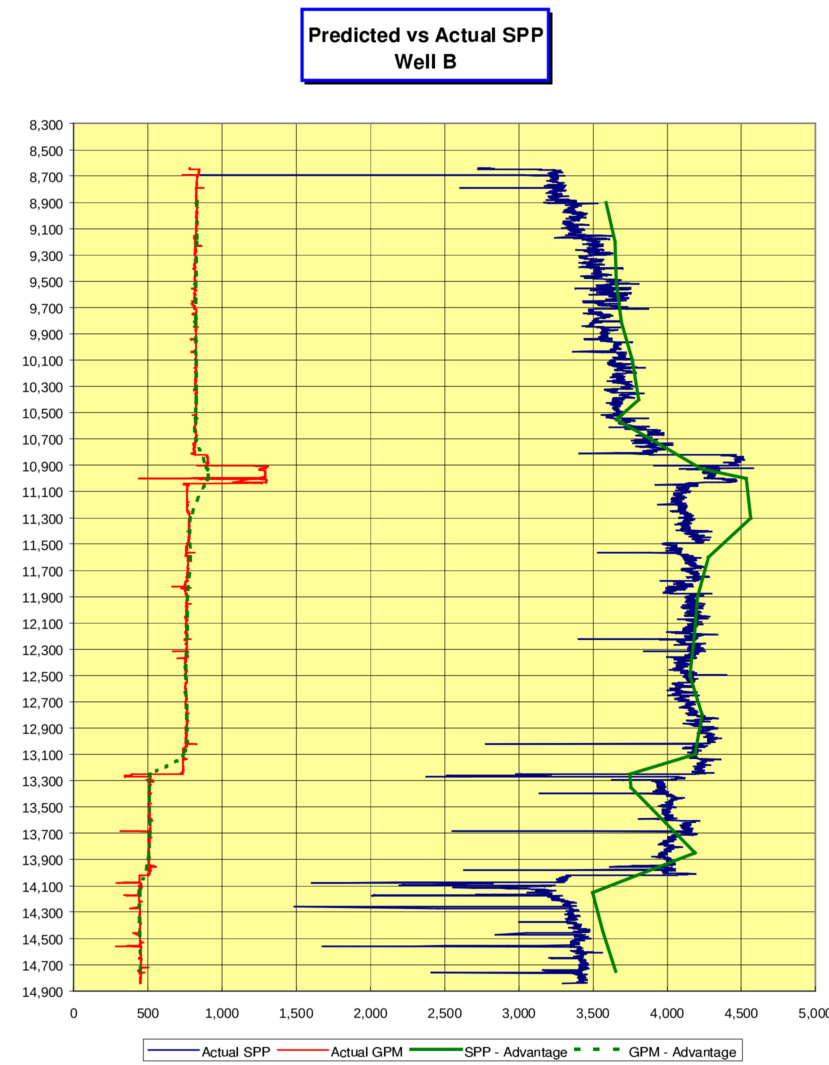


Figure 11. Actual vs Predicted Surface Pressure vs Depth – Well B