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Reverse Engineered Drilling Fluid Design for ERD and Ultra-ERD Operations

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Abstract

In areas where environmental and geographical constraints have prohibited the use of conventional drilling techniques, extended reach drilling (ERD) technologies have allowed operators to reach significant reserves while minimizing surface impacts. While the high-angle and horizontal intervals now exceed 30,000 ft measured depth (MD) in many operations, the true vertical depth (TVD) of most ERD wells generally ranges from about 6,000 ft to 9,000 ft.

However, even at these relatively shallow TVDs, the equivalent circulating density (ECD) on ERD wells requires careful management. It is not uncommon to see as variance of several pounds per gallon between the surface mud weight and the ECD. The high ECD is a function of the flow rates, conventional fluid properties and the extended length of the wells. Therefore, ERD operations pose similar challenges to those encountered in deepwater operations, with similar economic factors in play.

Designing a drilling fluid for ERD operations using sophisticated hydraulics modeling helps ensure that the fluid can offer sufficient carrying capacity while maintaining the lowest possible ECD at the desired pump rates. When modeled accurately, formulations that may intuitively seem correct for ERD conditions can demonstrate excessive ECDs or a strong propensity for sag. Therefore, the proposed formulations should undergo stringent hydraulics modeling, using FANN® 75/*iX*77 rheometer data (for simulating downhole rheological properties) and including anticipated pump rates, well geometries and penetration rates to identify the best fit for actual conditions. This paper presents the results of modeling a series of drilling fluid formulations intended for ultra-ERD wells and insights into fluid behavior under ultra-ERD conditions.

Introduction

In areas where environmental and geographical constraints limit the use of conventional drilling techniques, ERD technologies have allowed operators to develop significant reserves while minimizing surface impacts. The successful Wytch Farm development in southern England established the advantages of the ERD approach in the mid-1990s, and many record-breaking wells continue to be drilled each year at a variety of locations. For example, environmental sensitivity has led major operators on Russia's Sakhalin Island to drill numerous ERD wells, some with measured depths (MD) exceeding 35,000 ft. Wells located offshore Canada and California, where operations can be highly restricted, are also drilled successfully using ERD methods.

The operational challenges and economic factors presented by ERD wells are similar in several aspects to those associated with deepwater operations, but they arise from different conditions. Challenges include hole cleaning effectiveness and equivalent circulating density (ECD) control. Monitoring cuttings loading and carefully managing fluid hydraulics are essential to preserving wellbore stability. At least one major operator with wide ERD experience had challenged conventional models for hole cleaning, stuck pipe avoidance and tripping practices.[1]

The true vertical depth (TVD) of most ERD wells generally ranges from about 6,000 ft to 9,000 ft, although TVDs of 10,000 ft and greater are no longer rare. The comparatively shallow TVDs of some ERD wells may imply that controlling ECD will not be a significant issue, but the analysis of several ERD wells has proven otherwise. It is not uncommon to see a variance of *several pounds per gallon* between the surface mud weight and the ECD.

These high ECDs result from the flow rate requirements, the properties of fluids typically used on ERD wells, and the six-mile and longer horizontal displacements that many operators have achieved in the last 10 years. As with deepwater operations, rig time and daily spreadcosts can be quite high on ERD jobs. Operators constantly look for ways to minimize non-productive time (NPT) while accelerating the well construction process.

ERD Fluid Design Criteria

Designing a drilling fluid for ERD operations using sophisticated hydraulics modeling helps ensure that the fluid can offer sufficient carrying capacity while maintaining the lowest possible ECD at the desired pump rates. Considerations include adapting flow rates to the rate of penetration (ROP), minimizing surge pressures while tripping and running casing, and determining whether the downhole flow profile is laminar or turbulent based on a given set of hydraulic inputs. A major drilling fluids company began formulating and testing a series of oil-based drilling fluids for use in an ultra-ERD well.

The operator's criteria for the proposed well included the following:

- MD = 38,000+ ft

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*iX*77 HPHT Rheometer is a trademark of Fann Instrument Company.

- TVD = ± 5,000 ft
- Surface mud weight = 11.5 ppg
- Maximum ECD = 16.5 ppg
- Desired flow rate = 600 gpm
- Bottomhole temperature (BHT) = ± 200°F

On the previous well, the 11.3 ppg surface mud weight translated to a 16.4 ppg ECD at a pump rate of 585 gpm. The new criteria specified a maximum ECD of 16.5 ppg while pumping at a higher rate.

Reverse Engineering

It was recommended that all proposed formulations continue to undergo stringent hydraulics modeling using FANN® 75/*iX*77™ rheometer data (for simulating downhole rheological properties) and including anticipated pump rates, well geometries and penetration rates to identify the best fit for actual conditions.

One conventional approach to minimizing ECD is making the fluid thinner. It seems intuitive that the thinner the fluid, the lower the ECD values will be. However, the models developed with high-accuracy hydraulics modeling software showed that thinner fluids did not improve ECD at the pump rates required by the operator. Thinner fluids exhibited turbulent flow, and when evaluated with dynamic high-angle sag testing, the thinner fluids demonstrated a strong propensity for barite sag, making them unsuitable for ERD wells.

When modeling demonstrated that a thin fluid would fail to deliver the required performance, fluid designers took a different approach to their task—one that had aided in qualifying other fluids for exceptional service. Applying a reverse engineering strategy, they first modeled the properties needed to accomplish the objectives. The operator's 600-gpm flow rate requirements formed the basis of the investigation.

This method required a very high level of accuracy and reliability from the modeling software. Its accuracy was verified by specific field data from the preceding well and by extensive documentation acquired over a 10-year period. Long-term comparisons with pressure-while-drilling (PWD) values in the field had proven that the modeling software tracks very closely with actual ECDs—variances typically do not exceed 0.1 ppg—making it the right tool to aid in fluid development. If a fluid could be designed to allow the client to maintain 600 gpm, careful hydraulics management and accurate ECD forecasts would be essential both in the planning and execution stages.[2]

By first modeling the properties of an 11.5-ppg field mud sample from the offset well, the fluid designers could see the ECD at various depths and observe the cuttings loading. Even though the hole was being cleaned effectively so that cuttings were not contributing significantly to the ECD, a 4.9 ppg differential was predicted at 600 gpm (**Figure 1**).

The mud weights and flow rates from the actual well were consistent with these findings. As depth and horizontal displacment increased, the pump rate had to be reduced to prevent the ECD from exceeding the limit (**Figure 2**).

Designing an Oil-based System for ERD

Oil-based muds are typically the fluid of choice for ERD wells because they impart the necessary lubricity. As noted above, the first fluid modeled for the proposed well was designed based on the conventional thinking that a thinner fluid would offer improved ECD control. The components of these formulations are shown in **Table 1**. As per the client's specifications, a mineral oil base fluid was used. The initial formulations included one clay-free invert emulsion system, one conventional invert emulsion system and one "all-oil" system (with a 98/2 oil-water ratio).

However, as each fluid was modeled, it was apparent that the desired ECD results could not be achieved at the specified pump rate without moving from laminar to turbulent flow (**Figures 3-5**). Following this conclusion, the design process was switched to the "reverse engineering" mode. Rather than input the properties of actual fluids, the developers manipulated the inputs to achieve the desired outcome. In this fashion, the hydraulics modeling helped establish the primary target in terms of rheological properties. Once a fluid that exhibited these properties could be formulated, it could then be adjusted as needed to address other requirements such as lubricity, filtration control, temperature tolerance and resistance to contaminants. The optimized fluid also had to meet logistical and environmental standards for service in a remote, pristine area.

To achieve the goal, the developers began considering what materials could be removed from the formulation without sacrificing the "ideal" properties modeled by the hydraulics software. They applied some of the technologies used in high-performance oil-based systems that have been proved to help lower ECD and minimize downhole losses while providing effective hole cleaning. The "black powder" additives were removed. A polymeric filtration control additive that can act as a secondary viscosifier was used instead. The organophilic clay content was reduced by 50%. They also changed the oil/water ratio (OWR) from 80/20 to 70/30. The formulation is shown in Table 2.

When the surface properties of the optimized fluid are compared to the system used on the previous well, the differences in rheological properties are clear (**Table 3**). The yield points remain similar, but the gel strength and low-rheologies differ significantly, resulting in a desirable Tau 0 value. The high Tau 0 value suggests that this fluid has a very low sag potential. The 10-minute gel strength on the optimized is fluid is double that of the previous fluid so that the suspension qualities are very robust.

The properties of the optimized fluid were then subjected to another round of hydraulics modeling as well as advanced sag and rheology testing to confirm that the proposed fluid could meet all the demands presented by the upcoming ultra-ERD well.[3] The proprietary dynamic high angle sag test (DHAST™ apparatus) allows the fluid to be tested at varied shear rates at a 45° angle so that fluid behavior can be predicted under a wide range of conditions. The optimized fluid was tested and exhibited acceptable values for resistance

DHAST™ Testing Apparatus is a trademark of Baroid Fluid Services.

to sag.

Extensive rheology testing using a high-temperature/high-pressure (HPHT) rheometer indicated that the rheological properties remain stable throughout the anticipated wellbore conditions. Normally a fluid would be expected to thin with increased temperature, or thicken with increased pressure—therefore HPHT rheometer results can demonstrate how the fluid behaves when exposed to the combined effects of temperature and pressure. Hydraulics modeling using the actual properties of the optimized fluid indicated that not only would the ECD remain within specification at 600 gpm, but that the optimized fluid would provide a significantly lower ECD while meeting other requirements (**Figures 6-7**).

The fluid also exhibited a lower coefficient of friction than the previously used fluid, so that it met or exceeded the lubricity requirements.

Cost Factors

When a fluid system is custom-designed for a specific application, it can often be more expensive than the "off-the-shelf" systems on a cost per barrel basis. In ERD wells, the addition of treated weighting agents intended to help reduce ECD can also push costs up. However, the optimized fluid presented in this paper actually has a lower per barrel cost than other systems that were considered.

The change in OWR from 80/20 to 70/30 helped reduce base oil costs and logistical issues, and the removal of several additives also contributed to lower formulation and transport costs. As a result, the cost per barrel of the proposed optimized system was US$10 lower than the next least expensive alternative, and considerably lower than many ERD "designer" systems currently in use.

Conclusions

- Although conventional wisdom implies that "thin" fluids will be more effective at reducing ECD, this has not been the case in designing fluids for use in ERD and ultra-ERD applications.
- Thin fluids go into turbulent flow at or below 600 gpm.
- Maintaining the fluid in laminar flow at 600 gpm can significantly reduce the ECD.
- The "ideal" rheological properties for maintaining laminar flow should be obtained by modeling before any fluid is tested.
- The fluid can then be designed to provide the desired rheological properties with adjustments made to help ensure that all other mud properties are within specification.

Acknowledgments

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References

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Tables

Table 1. Initial Formulations for Proposed ERD Well (Thin Fluids)

Sample Mark	SYSTEM 1	SYSTEM 2	SYSTEM 3
Calculated Properties			
Mud weight, lb/gal	11.5	11.5	11.5
OWR	70/30	70/30	98/2
WPS, ppm CaCl2	275,000	275,000	275,000
Emulsifier, lb	10	6	3
Lime, lb	3	3	3
Organophilic Clay, lb	---	2.5	8
Leonardite Filtration Control Additive, lb	---	5	---
Polymer Filtration Control Additive, lb	2	---	---
Polymer Filtration Control Additive, lb	---	---	2
TAU-MOD, lb	10	---	---
Viscosifier, lb	2	---	---
Rheology Modifier, lb	0.5	0.3	0.6
Plastic viscosity, cP	23	16	13
Yield point, lb/100 ft2	12	14	15
10 Sec gel, lb/100 ft2	4	8	14
10/30 Min gel, lb/100 ft2	11 / 15	10 / 14	30 / 36
Fann 35 dial readings @ 120°F			
600 rpm	58	46	41
300 rpm	35	30	28
200 rpm	25	23	23
100 rpm	17	15	18
6 rpm	5	6	12
3 rpm	4	5	10

Table 2. Optimized Formulation for Proposed ERD Well

Mud weight, lb/gal	11.5
OWR	70/30
WPS, ppm CaCl2	250,000
Escaid 110 oil, bbl	0.56
Emulsifier, lb	7
Lime, lb	3
Organophilic Clay, lb	4
Polymeric Filtration Control Additive, lb	2.5
Water, lb	0.25
Calcium chloride, lb	30
Rheology Modifier, lb	0.6
Barite, lb	194

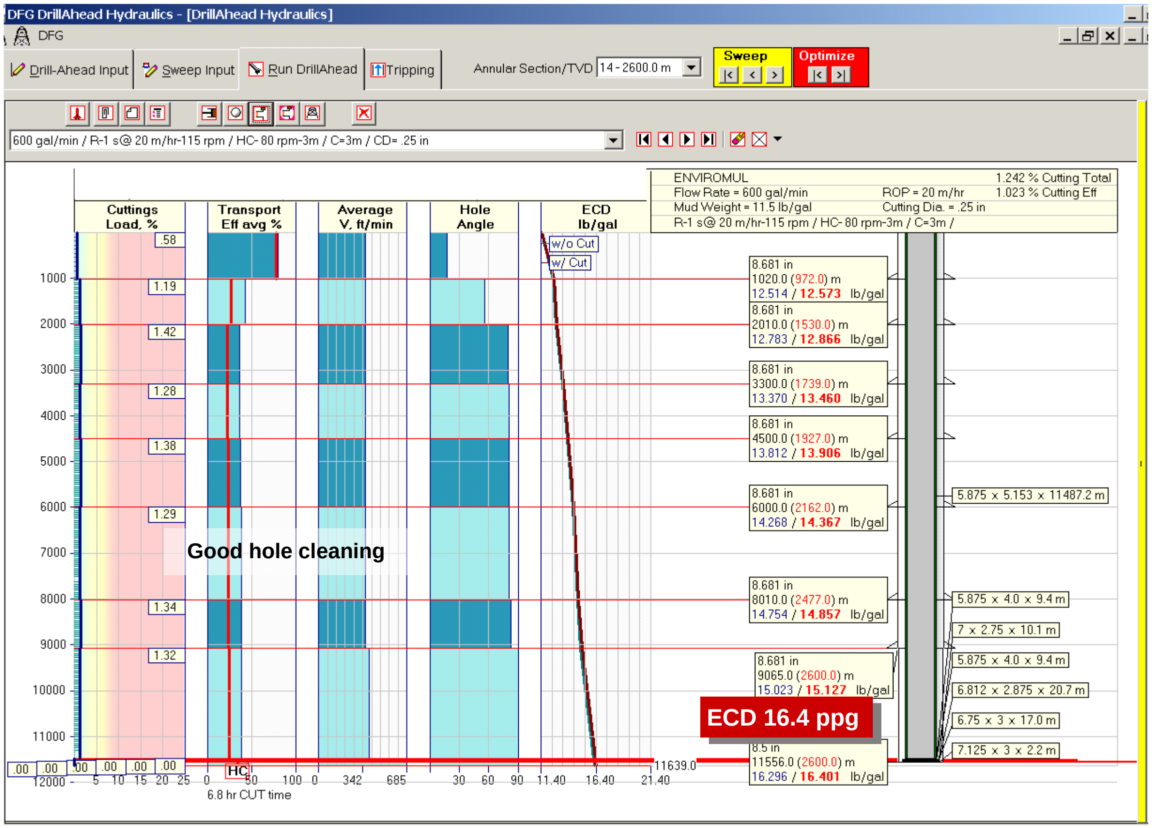
Table 3. Comparison between Optimized Fluid Surface Properties and Surface Properties of Fluid Used on Previous Well

PROPERTIES	OPTMIZED FLUID	FLUID USED ON OFFSET WELL
Plastic Viscosity, cP	18	26
Yield Point, lb/100ft2	16	14
10-sec Gel, lb/100ft2	14	9
10/30 Min Gel, lb/100ft2	20 / 23	10 / 12
Electrical Stability @ 120°F, v	981	550
Fann 35 Dial Readings @ 120°F		
600 rpm	52	66
300 rpm	34	40
200 rpm	28	30
100 rpm	20	20
6 rpm	11	7
3 rpm	10	6
n	0.799	0.815
K	0.173	0.224
Tau 0, lb/100ft2	10.00	5.57

Table 4. Optimized Fluid Rheological Properties (FANN 35 and FANN *iX*77 HPHT Rheometer)

Fann Model	35	77						
Temperature, °F	120	120	120	120	120	175	225	250
Pressure, psi	0	0	2500	5000	7500	2700	5000	7500
600 rpm	52	50	56	63	70	48	49	50
300 rpm	34	33	38	42	47	33	33	34
200 rpm	28	28	31	35	38	28	28	28
100 rpm	20	22	24	26	28	22	22	23
6 rpm	11	14	14	15	16	13	13	13
3 rpm	10	14	14	14	15	11	12	12
Plastic viscosity, cP	18	17	18	21	23	15	16	16
Yield point, lb/100 ft2	16	16	20	21	24	18	17	18
n	0.799	0.928	0.844	0.793	0.791	0.735	0.788	0.770
K	0.173	0.059	0.124	0.210	0.242	0.232	0.162	0.189
Tau 0, lb/100 ft2	10.00	14.92	14.85	13.94	14.69	11.57	12.28	12.19

Figures



Annular Section/TVD 14 - 2600.0 m

600 gal/min / R-1 s@ 20 m/hr-115 rpm / HC- 80 rpm-3m / C=3m / CD= .25 in

ENVIROMUL		1.242 % Cutting Total
Flow Rate = 600 gal/min	ROP = 20 m/hr	1.023 % Cutting Eff
Mud Weight = 11.5 lb/gal	Cutting Dia. = .25 in	
R-1 s@ 20 m/hr-115 rpm / HC- 80 rpm-3m / C=3m /		

8.681 in
1020.0 (972.0) m
12.514 / 12.573 lb/gal

8.681 in
2010.0 (1530.0) m
12.783 / 12.866 lb/gal

8.681 in
3300.0 (1739.0) m
13.370 / 13.460 lb/gal

8.681 in
4500.0 (1927.0) m
13.812 / 13.906 lb/gal

8.681 in
6000.0 (2162.0) m
14.268 / 14.367 lb/gal

8.681 in
8010.0 (2477.0) m
14.754 / 14.857 lb/gal

8.681 in
9065.0 (2600.0) m
15.023 / 15.127 lb/gal

8.5 in
11556.0 (2600.0) m
16.296 / 16.401 lb/gal

5.875 x 5.153 x 11487.2 m
5.875 x 4.0 x 9.4 m
7 x 2.75 x 10.1 m
5.875 x 4.0 x 9.4 m
6.812 x 2.875 x 20.7 m
6.75 x 3 x 17.0 m
7.125 x 3 x 2.2 m

6.8 hr CUT time

Figure 1 Hydraulics modeling output for 11.5 ppg field mud sample

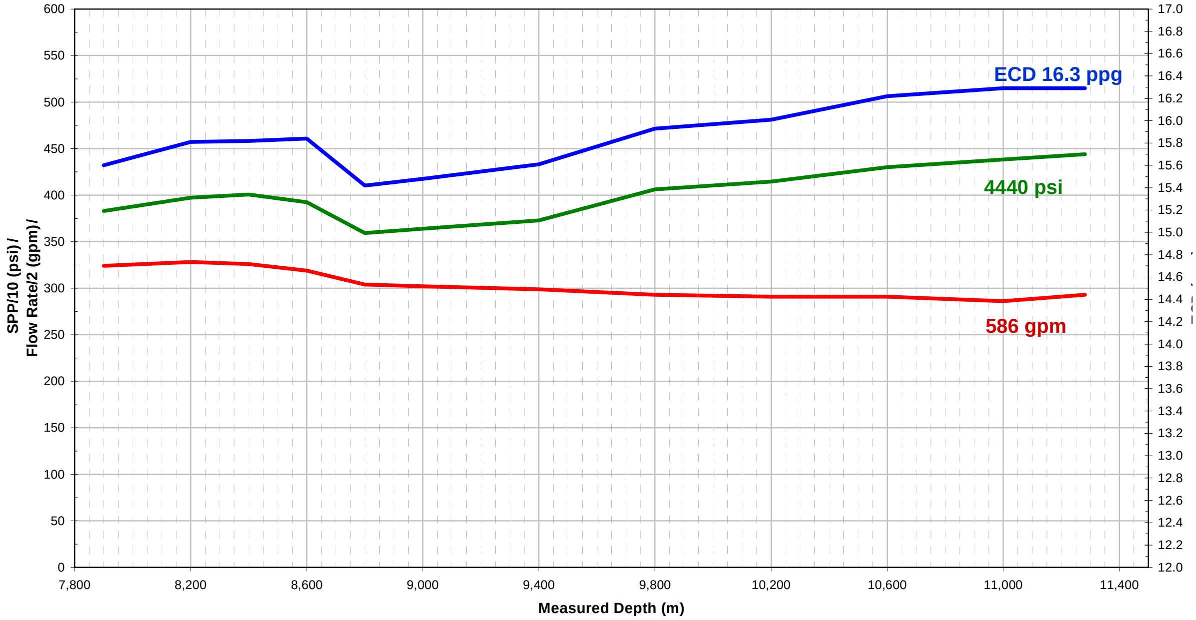
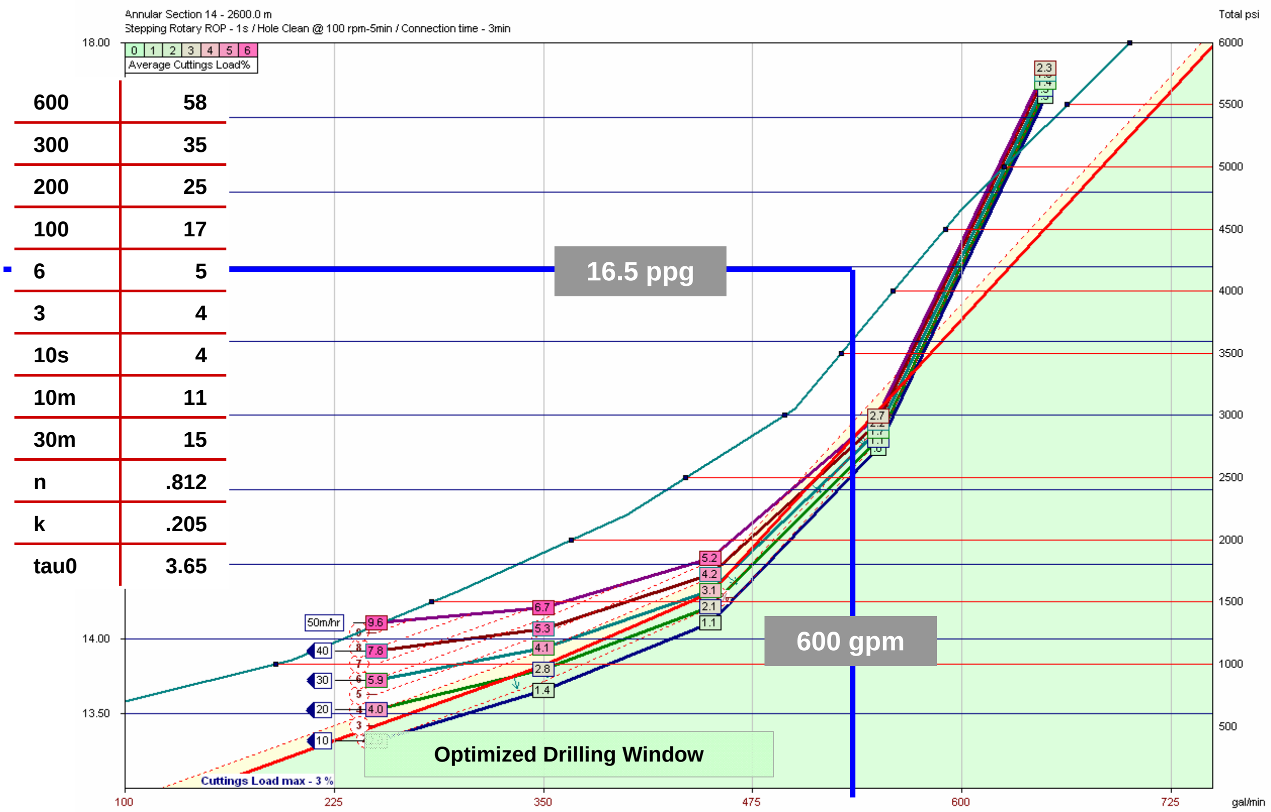
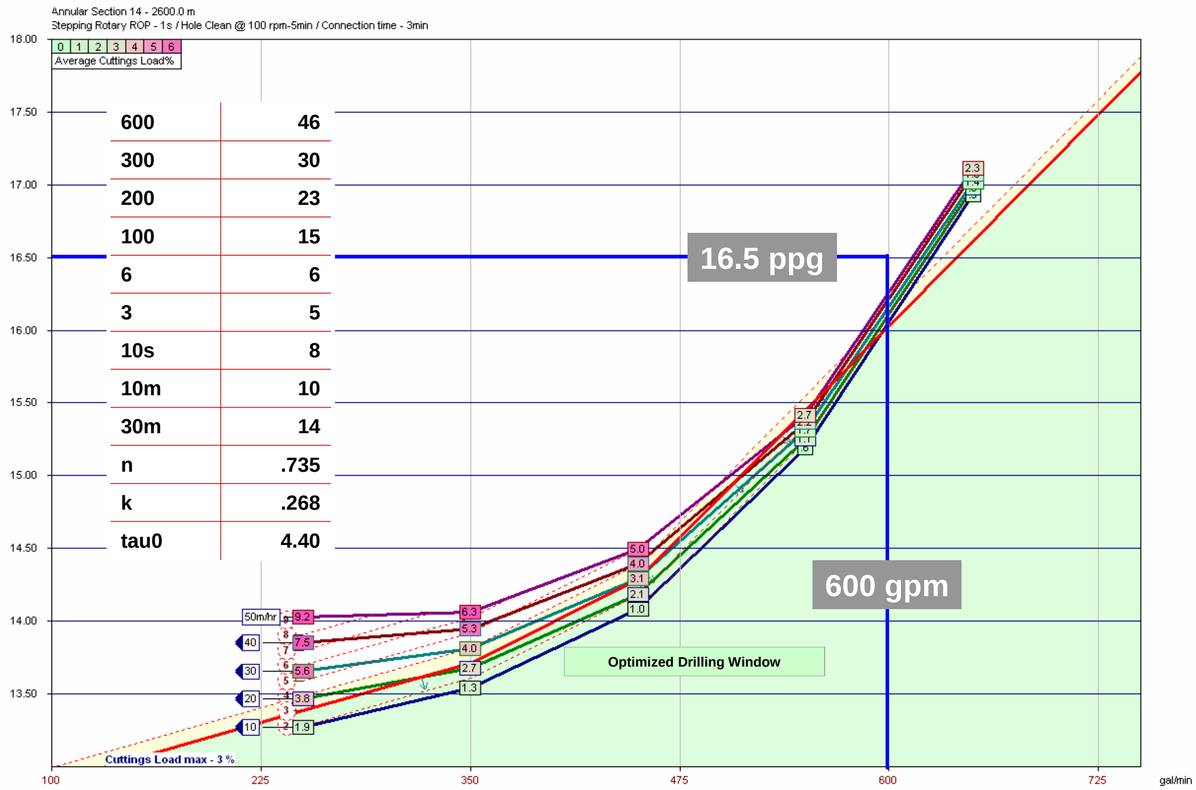


Figure 2 ECD vs depth vs flow rate in offset well



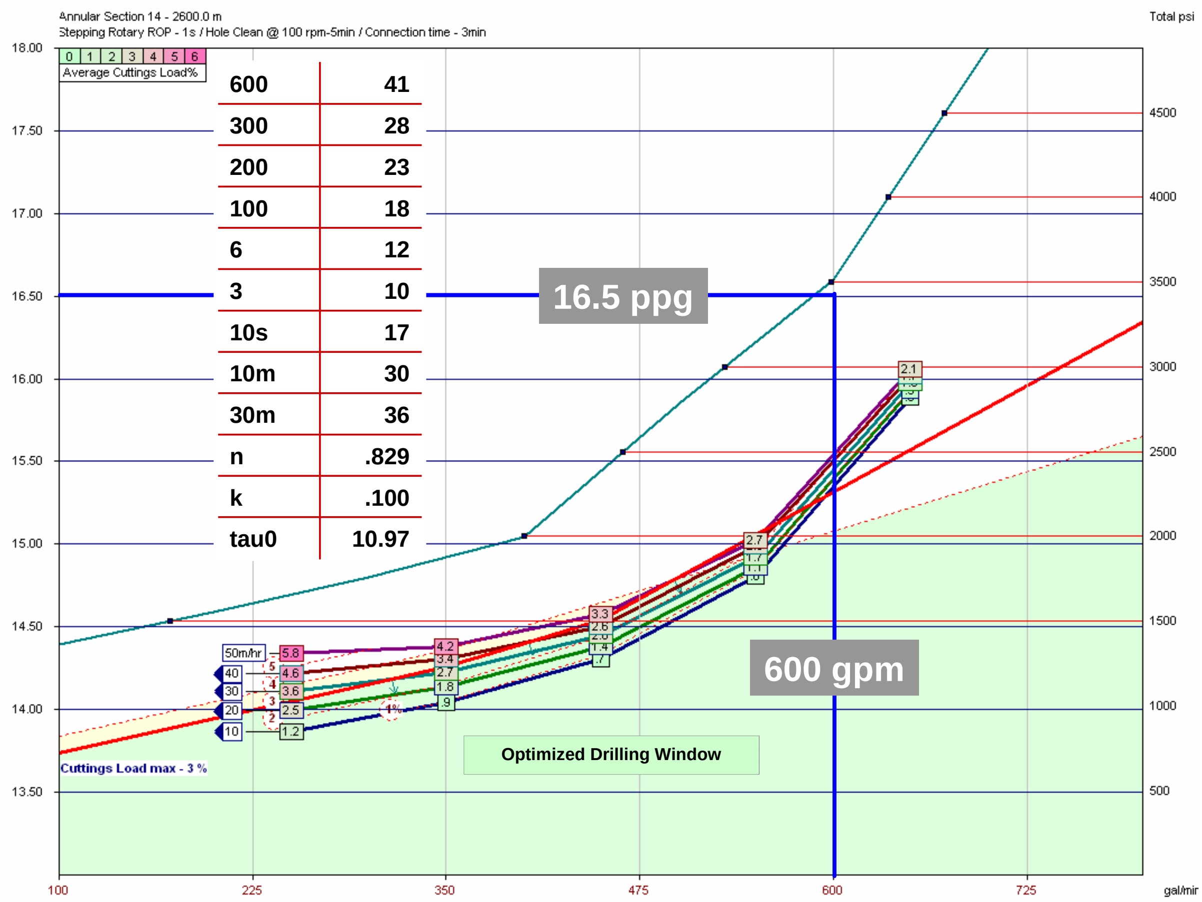
600	58
300	35
200	25
100	17
6	5
3	4
10s	4
10m	11
30m	15
n	.812
k	.205
tau0	3.65

Figure 3 Modeling at 600 gpm with System 1 (initial “thin” fluid formulations)



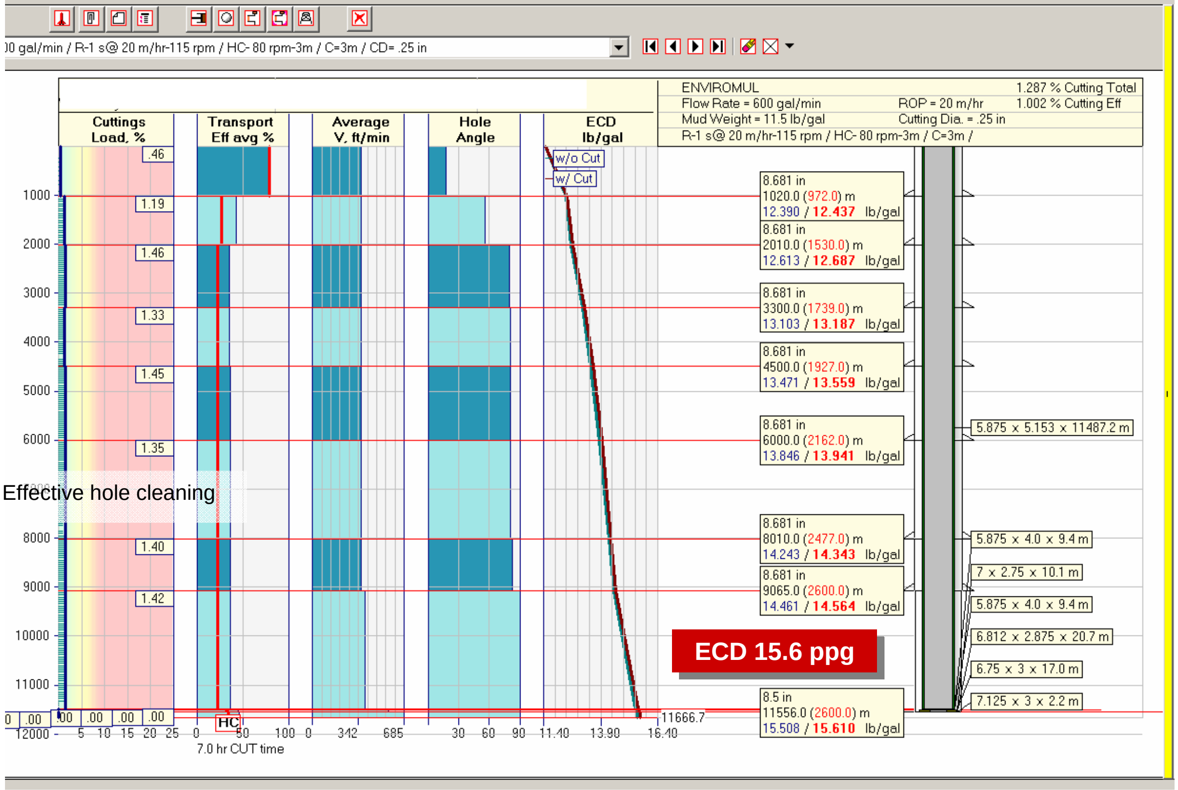
600	46
300	30
200	23
100	15
6	6
3	5
10s	8
10m	10
30m	14
n	.735
k	.268
tau0	4.40

Figure 4 Modeling at 600 gpm with System 2 (initial “thin” fluid formulations)



600	41
300	28
200	23
100	18
6	12
3	10
10s	17
10m	30
30m	36
n	.829
k	.100
tau0	10.97

Figure 5 Modeling at 600 gpm with System 3 (initial “thin” fluid formulations)



0 gal/min / R-1 s@ 20 m/hr-115 rpm / HC- 80 rpm-3m / C=3m / CD= .25 in

ENVIROMUL — 1.287 % Cutting Total

Flow Rate = 600 gal/min — ROP = 20 m/hr — 1.002 % Cutting Eff

Mud Weight = 11.5 lb/gal — Cutting Dia. = .25 in

R-1 s@ 20 m/hr-115 rpm / HC- 80 rpm-3m / C=3m /

8.681 in
1020.0 (972.0) m
12.390 / 12.437 lb/gal

8.681 in
2010.0 (1530.0) m
12.613 / 12.687 lb/gal

8.681 in
3300.0 (1739.0) m
13.103 / 13.187 lb/gal

8.681 in
4500.0 (1927.0) m
13.471 / 13.559 lb/gal

8.681 in
6000.0 (2162.0) m
13.846 / 13.941 lb/gal

8.681 in
8010.0 (2477.0) m
14.243 / 14.343 lb/gal

8.681 in
9065.0 (2600.0) m
14.461 / 14.564 lb/gal

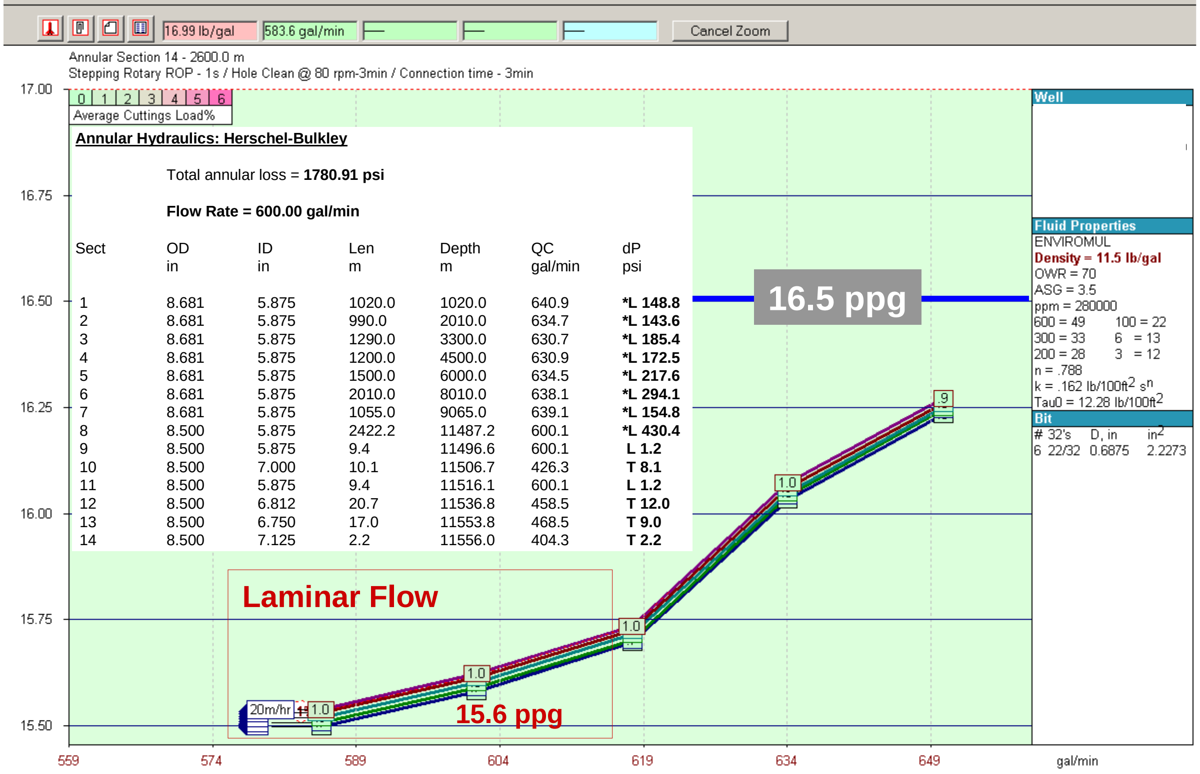
8.5 in
11556.0 (2600.0) m
15.508 / 15.610 lb/gal

5.875 x 5.153 x 11487.2 m
5.875 x 4.0 x 9.4 m
7 x 2.75 x 10.1 m
5.875 x 4.0 x 9.4 m
6.812 x 2.875 x 20.7 m
6.75 x 3 x 17.0 m
7.125 x 3 x 2.2 m

Effective hole cleaning

ECD 15.6 ppg

Figure 6 Optimized fluid provides effective hole cleaning with 15.6 ppg ECD



Annular Section 14 - 2600.0 m

Stepping Rotary ROP - 1s / Hole Clean @ 80 rpm-3min / Connection time - 3min

Annular Hydraulics: Herschel-Bulkley

Total annular loss = **1780.91 psi**

Flow Rate = 600.00 gal/min

Sect	OD in	ID in	Len m	Depth m	QC gal/min	dP psi
1	8.681	5.875	1020.0	1020.0	640.9	***L 148.8**
2	8.681	5.875	990.0	2010.0	634.7	***L 143.6**
3	8.681	5.875	1290.0	3300.0	630.7	***L 185.4**
4	8.681	5.875	1200.0	4500.0	630.9	***L 172.5**
5	8.681	5.875	1500.0	6000.0	634.5	***L 217.6**
6	8.681	5.875	2010.0	8010.0	638.1	***L 294.1**
7	8.681	5.875	1055.0	9065.0	639.1	***L 154.8**
8	8.500	5.875	2422.2	11487.2	600.1	***L 430.4**
9	8.500	5.875	9.4	11496.6	600.1	**L 1.2**
10	8.500	7.000	10.1	11506.7	426.3	**T 8.1**
11	8.500	5.875	9.4	11516.1	600.1	**L 1.2**
12	8.500	6.812	20.7	11536.8	458.5	**T 12.0**
13	8.500	6.750	17.0	11553.8	468.5	**T 9.0**
14	8.500	7.125	2.2	11556.0	404.3	**T 2.2**

16.5 ppg

Laminar Flow

15.6 ppg

Well

Fluid Properties

ENVIROMUL

Density = 11.5 lb/gal

OWR = 70

ASG = 3.5

ppm = 280000

600 = 49 100 = 22

300 = 33 6 = 13

200 = 28 3 = 12

n = .788

k = .162 $lb/100ft^2\ s^n$

Tau0 = 12.28 $lb/100ft^2$

Bit

# 32's	D, in	in^2
6 22/32	0.6875	2.2273

Figure 7 Maintaining fluid in laminar flow reduced ECD at 600 gpm