AADE-05-NTCE-28

The Pro's and Con's of Flat Rheology Drilling Fluids

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Abstract

Drilling fluid companies continually pursue "cutting edge" technology to improve drilling performance and gain a competitive edge. This innovation is driven by the growing complexity of challenges undertaken by operators to reach increasingly remote reserves while reducing operational costs. Both the environmental and performance characteristics of synthetic-base drilling fluids (SBM) make them almost ideal for addressing these challenges and they are particularly well suited for deep water operations. However, while drilling in deep water in the Gulf of Mexico losses of fluids down hole can result in substantial costs for an operator.

An approach to reduce drilling fluid losses when drilling deepwater wells is the advancement of "Flat Rheology" drilling fluid systems. It is widely accepted that the design of a drilling fluid program should be based upon fluid measurements taken under down hole and surface conditions. These pressure-temperature measurements can then be input into validated hydraulics models to plan and execute a drilling operation.[4-7] The use in the drilling industry of the term "Flat Rheology" to describe an emulsion-based drilling fluid viscosity measured under atmospheric conditions is reviewed in this paper.

Introduction

Losses of drilling fluids during wellbore construction occur during a variety of operations including drilling, running casing or drilling assembly to bottom (tripping), and cementing. Drilling losses are usually related to the equivalent circulating density (ECD) exceeding the fracture gradient. Tripping and cementing losses are related to a combination of ECD, the pressure necessary to break the drilling fluid gel structure, and the equivalent static density at the time of the operation.

A creative technique to manipulate the drilling fluid system's degree of viscosity fluctuation under down hole conditions has been used in an effort to reduce drilling fluid losses. This approach is reported to minimize the "unknowns" associated with drilling fluid behavior and is often referred to as "Flat Rheology" or an "apparent flat yield point" drilling fluid system.

High performance has been reported using such a technique. These synthetic-based fluids are formulated with modified emulsifiers, polymeric rheological modifiers and "minimal" amounts of organophilic clay. It has been reported that such a fluid could be designed with an elevated "flat" rheological properties profile, as compared to a "conventional" synthetic-based mud, yet provide a lower ECD, better hole cleaning and barite suspension, reduced down hole mud losses during cementing operations, running casing and drilling.[1,2]

Other claims have been made that a rheological profile without the use of "any" organophilic clay additive can provide excellent hole cleaning, lower ECD, elimination of barite sag, reduced down hole losses and overall improved fluid-related drilling efficiency compared to a conventional drilling fluid system. These benefits have been reportedly achieved with higher viscosity than a conventional system. [1, 2, 3]

This paper describes methods used to achieve a "flat" yield point profile, presents viscometer measurements taken under down hole conditions of field muds with this type of profile, and provides comparisons of hydraulic simulations with the "Flat" system to a conventional shear thinning deepwater system.

The flat yield point SBM (Flat) field mud reviewed in this paper was provided by a customer for laboratory analysis. The properties are representative of other field and laboratory Flat systems. The conventional deep water SBM system (Conventional) was also a field mud.

Design Considerations for Flat Systems

The terms "Flat Rheology" and "Flat Yield Point" describing a drilling fluid are concepts recently introduced to the drilling industry. The concept originated from the attempts to eliminate drilling mud losses while running casing and liners in deepwater wells. It was thought that if a drilling fluid had "near" constant yield point under low temperature and high pressure as well as with increased temperature and high pressure, accuracy in predicting the behavior of pressure response while tripping pipe would be improved thus eliminating or minimizing down hole losses.

This is a concept warranting further effort. Accordingly, drilling fluid companies pursued the Flat system. An idealized Flat system is reviewed in this paper, which confirms that the Flat system approach would minimize ECD under many cases. However, the ability to control a flat viscosity profile is influenced by several mechanisms that cannot always be controlled. These influences include the variables of temperature, pressure, the interaction of rheological modifiers and drill solids, changing shear rate in the annulus, variations in alkalinity, and rheological modifier concentration changes.

A list of drilling fluid components used for formulating a Conventional synthetic and a Flat synthetic system is presented in **Table 1**. Several components of the drilling fluid can influence the ability to generate a flat profile, and the most influential are discussed below.

Base Fluid: One of the main challenges in designing a deepwater synthetic fluid is to reduce the overall viscosity of the fluid at low temperatures and increased pressures. Due to the viscosity and chemistry of the base fluids used in synthetic-based drilling fluids, large variations in rheological properties are often evident under down hole conditions, especially when compared to the properties in the riser.

The most significant viscosity impact is observed at lower temperatures and elevated pressure and is where the viscosity of each base fluid most impacts the “whole mud” viscosity. Some base fluids exhibit much higher viscosity than others under identical conditions (**Figure 1**). The compressibility of the base fluids will also impact the viscosity of the whole mud, when exposed to down hole conditions [8].

The starting point for generating a Flat system is the choice of the appropriate base fluid. A base fluid with a low, flat kinematic viscosity versus temperature, will allow the usual parameters of interest, Bingham Yield Point, 6 and 3 rpm oilfield viscometer readings, to be achievable at the lowest possible values.

Viscosifier: Historically organophilic clays have been the most common viscosifier for invert emulsion based systems. There are numerous organophilic clays available. These clay viscosifiers range from relatively inexpensive dry processed bentonite to the more costly wet processed hectorite clays. Performance differences are predominantly observed in the ability to provide viscosity at low shear rates and their ability to endure high temperature conditions.[12]

A drilling fluid system formulated with organophilic clay as the primary viscosifier will exhibit a reduction in viscosity with increasing temperature, when measured with a conventional oilfield six speed viscometer at atmospheric pressure. Therefore, if the objective is to demonstrate a constant yield point or low shear viscosity, under atmospheric conditions with increased temperature, the use of organophilic clay must be supplemented with rheological modifiers.

Increasing pressure will increase the viscosity of an invert emulsion drilling fluid system. Often, down hole pressure will affect a system formulated with organophilic clay and a compressible base fluid by increasing the viscosity thus counteracting the viscosity reduction caused by increased temperature. This is particularly evident at temperatures between 40°F and about 80°F. A Conventional fluid made with organophilic clay will regularly demonstrate relatively flat viscosity curves when measured under down hole temperatures and pressures, except in the cold riser. **Figure 2** illustrates the viscosity properties of two conventional field SBM’s: one is a low density, low Synthetic-Water Ratio (SWR) fluid and the other is a higher density and higher SWR fluid. The YP is relatively flat with the exception for conditions in the riser, where low temperature and high pressure exist. This is also demonstrated in Figure 13, discussed later.

Rheological Property Modifiers: It is possible to formulate an SBM with near constant yield point and low RPM viscometer dial readings measured on an oil field viscometer. This is accomplished by eliminating, or using a very low concentration of organophilic clay, and adding polymeric and/or surfactant rheological modifiers, which have a positive effect at a constant pressure and increasing temperature. The resulting viscosity is dependant on the concentration of rheological modifiers and alkalinity of the brine phase.

There are two approaches to achieve a Flat effect. One approach is to use low concentrations of organophilic clays combined with polymeric rheological property modifiers. These polymeric rheological property modifiers are “coiled” at low temperature with no affect on viscosity being observed. The polymers will expand and increase in length as the temperature rises. When the temperature is reduced the polymer contracts and the viscosity from the clay again becomes predominant.

Another approach is to use temperature activated surfactants that interact with the low concentration of clay and build viscosity networks and structure by interaction. The ability to build these networks is more efficient as the temperature is increased and less efficient as the temperature decreases. Therefore, the viscosity reduction from increased temperature will be compensated by the viscosity generated from the surfactant / clay networks built. Common to both approaches is that there exists a transition temperature where the loss of viscosity from clay or solids interaction is not fully offset by the activation of the polymeric viscosifier or rheological properties modifier. This could explain why Flat systems tend to exhibit “U” shaped viscosity curves when plotted against temperature at ambient pressure. This trend has been shown in earlier publications and is similar to that in **Figure 6**. [1, 2]

Testing of field fluids reveals that there exists a maximum temperature at which the reversible effect of the temperature activated viscosity described above will be lost, resulting in changes in the viscosity profile and reduced filtration control. **Figure 3** demonstrate the effect on filtration control of an 11.0 lb/gal Flat system by changing the API HPHT filtration control temperature from 200°F to 250°F. At 200°F the Flat field mud performed comparable to a Conventional field mud. But at 250°F the filtration increases dramatically and significant water breakout was observed.

Figure 4 displays various yield point profiles achieved by varying the type and concentration of rheological modifier. **Figure 5** is an example of one of the fluids in Figure 4 to which a fatty acid rheological property modifier was added. The effects of lime additions on the yield point profile were then evaluated. It can be observed from these figures that several profiles are achieved and the profiles change as the concentrations vary. Therefore, without a quantitative polymer/surfactant concentration analytical procedure, engineering the system at the rig site could be problematic.

Viscosity Measurements: Most published literature on flat rheology fluids demonstrates a flat system YP, while varying temperature at ambient pressure. The results from measuring viscous properties at 40°F, 100°F, 120°F and 150°F under ambient pressure conditions are a consideration for the field engineers. The flat profile at ambient pressure is not used for hydraulic simulations, unless the fluid retains these properties under down hole conditions.

Field supplied Flat and Conventional systems tested under surface and down hole conditions in a pressured viscometer are shown in **Figures 6** and **7**. In Figure 6, the Conventional fluid demonstrates the expected decrease in yield point, with increased temperature and atmospheric pressure conditions. Figure 7 illustrates measured data under the typical Gulf of Mexico deep water drilling temperature and pressure conditions. The Flat system reveals a flat yield point profile. However, the overall readings are elevated for an 11.0 lb/gal Flat fluid when compared to a Conventional fluid. The Conventional fluid also demonstrates a flat yield point profile under these conditions, except at the very low temperature.

Importance of Pressure - Temperature Measurements for Fluid Design

Drilling Fluid Components: It can be difficult to predict the down hole viscosity of a drilling fluid containing compressible components without sufficient input data. Complicating factors include:

- the type and quantity of additives used in the drilling fluid for a given application,
- multiple chemistries available to achieve functionalities such as viscosity, filtration control, and emulsion stability, and
- the unique compressibility characteristics of the multiple synthetic and oil base fluids available in the market.

Drilling fluid companies have a variety of organophilic clays, emulsifiers, fluid loss additives, thinners, low shear rate viscosity modifiers, and additional products to formulate and maintain emulsion drilling fluids. These additives may or may not have the same effect on viscosity under down hole conditions. This makes it impossible to accurately predict (model) how viscosity will respond with temperature and pressure. Therefore, it is necessary to actually measure the fluid's response to temperature change under down hole conditions using a pressurized viscometer. This data can then be used as input data for maximum accuracy in hydraulics and hole cleaning models. **Figures 8** and **9** illustrate this point. Figure 8 shows typical viscosity properties of identical SBM drilling fluids with respect to SWR, base fluid and density. One fluid is formulated with high performance organophilic clay (HPOC), while the other is formulated with a fatty-acid rheological modifier (FARM). The Bingham PV and YP, YZ (low shear rate yield point) and the 6 and 3 rpm readings are identical at measurements taken under atmospheric pressure at 120°F.

Figure 9 shows results of the same fluids measured under down hole pressure and temperature conditions. The fatty-acid low shear rate viscosity modifier increases the viscosity above the HPOC fluid under the same pressure and temperature conditions by as much as 104.5% on the low shear rate viscosity and up to 43% on the high shear rate viscosity. This example further demonstrates the variable effect of temperature and pressure on different emulsion-based fluid compositions and the value of viscosity measurement with temperature and pressure.

Compressibility: All synthetic and oil-based fluids are compressible, but not to the same degree. The base oil compressibility will have an effect on the pressure profiles along a wellbore. Pressure, volume and temperature (PVT) response of fluids components and the whole mud composition must be known to predict accurate down hole pressures or equivalent static density of the fluid. **Figures 10** and **11** illustrate examples of the large variance in density possible by changing oil type, temperature, and pressures. Figure 10 shows the wide variance in the density of base fluids used in emulsion-based systems. Figure 11 is a single base fluid, demonstrating the variance of density with pressure and temperature. Each base fluid will have a unique set of temperature and pressure characteristics.

Dynamic Pressures: Dynamic pressures, including ECD, surge and swab, are influenced by both compressibility of the whole drilling fluid and frictional pressure losses resulting from the effective viscosity along the wellbore. Whether drilling or tripping, the down hole viscosity of the fluid plays a major role in the overall ECD. The system gelling characteristics have an effect on dynamic pressures when running pipe, with the highest impact observed during extended static periods prior to running long sections of casing. Because of the effect of temperature on drilling fluid viscosity, accurate dynamic temperature models are critical to the prediction of down hole fluid properties. The pressure and temperature relationship that optimizes the drilling fluid's viscosity profile is then used to model, plan and execute a successful drilling project.

The Importance of Minimizing Viscosity Obtained using non-Organophilic Clay Materials

Weighting Material Sag: When a higher density particle is suspended in a fluid that has a lower density than the particle, settling occurs. The resulting down hole density stratification in drilling fluids can result in costly delays. Not only will drilled cuttings and barite settle, but high density brine will tend to stratify in an invert emulsion fluid.

Fortunately, the rate of settling is controllable. Bern et al [9] recognized that increasing low shear viscosity normally helps reduce dynamic sag but was dependant on the type of viscosity modifier used. Their conclusion was that “clay” type products were more effective than fatty acids. Mullen et al [10] concluded that clay based chemistries performed better than fatty acid viscosity modifiers at increasing ultra-low shear rate viscosity and gel structure, which minimizing dynamic barite sag. Tehrani et al [11] supported these author’s conclusions that dynamic sag was lower in clay-based SBM than in polymeric-based SBM. This approach reduced dynamic barite sag and minimized the negative impact on the ECD from an increase in the drilling fluids low shear rate viscosity by improving the rheological properties of the drilling fluid.

During deep water operations, weighting material settling is rarely reported. Many wells drilled in deepwater are vertical and barite sag is not expected. However, in deep water development drilling, the cooler circulating temperatures experienced may result in a fluid viscosity such that sag is not occurring to a noticeable degree. Sag may be occurring but not detected since there is a large volume of “boosted” riser fluid which may mask barite sag occurring in the deeper sections of the wellbore. A true understanding of the drilling fluid rheological properties under down hole conditions is critical to maintaining a sag controlled system.[12]

The Importance of Viscosity for Hole Cleaning

Cuttings Removal: Removal of the cuttings from the well is dependent on many variables including the flow rate, cuttings density and size, and cuttings agglomeration. Cuttings removal is dependent on ROP, the inhibitive nature of the drilling fluid, the fluid density and viscosity, the wellbore angle and geometry, and pipe rotation. Sifferman and Becker [13] and others have concluded from that a fluids viscosity had a “moderate” impact on hole cleaning. The major factors were mud density, annular velocity, drill pipe rotation and hole angle.

Focus on YP and viscosity alone to ensure adequate hole cleaning is not practical without considering the overall situation. For example, some operations require low viscosity fluids and rely on high annular velocities to clean the wellbore while others require drilling with lower annular velocities with a more viscous fluid. Considerations to the drilling rig capabilities, pore pressure / fracture pressure margin, hole size and angle, operational procedures, need consideration before formulating an all encompassing approach to ensure adequate cuttings removal with respect to the drilling fluids viscosity profile.

Viscosity and ECD: The Relation to Shear Rate

For the purpose of this discussion the Power Law, Herschel-Bulkley and Robertson-Stiff viscosity models have similar characteristics that affect pressure loss calculations. With a constant annular volume, a change in flow rate changes the annular velocity and the effective shear rate, thereby changing the effective viscosity. Conversely, keeping flow rate constant and altering the annular geometry, the effective shear rate changes, resulting in a change in effective viscosity. Pressure losses are dependent on the effective viscosity of the fluid, which is dependent on the fluid shear rate. This only considers the “mechanical” aspect of variables that shape the viscosity curve. As discussed earlier, pressure and temperature will affect viscosity and must be included in computer models.

Because of this viscosity dependency on shear rate, or flow rate, drilling fluids are described as non-Newtonian or shear thinning fluids. **Figure 12** illustrates viscosity profiles for a Newtonian fluid and a typical non-Newtonian drilling fluid. Note the slope of the viscosity curve of the drilling fluid changes dramatically at the low end of the shear rate range between approximately $5s^{-1}$ and $200s^{-1}$ or 3 rpm to 120 rpm on a six speed oil field viscometer. This is an important characteristic with regard to ECD modeling and management during drilling operations. In most cases, the shear rates experienced during drilling and casing operations are usually within a shear rate range equivalent to less than a 200 rpm equivalent six speed viscometer dial reading.

In **Figure 12** the viscosity curve begins to approach a steady value at the higher shear rates. It is the higher shear rate ranges from which the Bingham Plastic Viscosity and Yield Point are derived. Because high shear rates are typically experienced in the drill pipe, the higher shear rate viscosity measurements have their greatest impact on stand pipe pressure (SPP). Since annular fluid velocity and shear rates are relatively low in most deepwater drilling operations, high shear rate viscosity values do not have an impact on the pressure loss in the annulus and the resulting effect on the ECD.

Flat Rheology Fluid: Evaluation

Hydraulics Evaluation: The use of drilling fluid databases and/or modeling a fluids dial readings to “estimate” the effect on viscosity under down hole conditions is not recommended, as the fluid’s rheological properties are constantly changing throughout a well. Accordingly, it is recommended that samples from the field be tested using pressurized viscometers with the temperature and pressures for the well being drilled. This data can then be used for hydraulic simulations.

Current hydraulics models result in excellent predictions of down hole viscosity and pressure loss.[4, 6, 14] This precise modeling is achievable because of accurate density and viscosity algorithms based on PVT data which predict the down hole density of base fluids, combined with the input of field drilling fluid effective viscosities determined under down hole conditions. These inputs coupled with accurately modeled temperature profiles result in correct down hole pressure modeling.

Several hydraulics comparisons of a Flat and Conventional drilling fluids were performed using validated hydraulics software incorporating the Herschel-Bulkley fluid model. The evaluations were intended to assess the potential for a lower ECD with the application of a Flat system. The analysis was performed with a hydraulics model that considers pressure and temperature effects on fluid density and viscosity every 100 feet, or less, to improve the accuracy of results. All variables that influenced the modeling results, with exception of the drilling fluids viscometer readings, remained the same during the comparison of the two fluids. The differences in ECD values were due solely to the variation in the fluid viscosity values used in the model.

Figures 13 and 14 show results of a simulation of a 12-1/4 inch hole section below 11-7/8 inch casing, in a vertical deepwater well located in the Gulf of Mexico. The well was drilled in approximately 7,400 feet of water with 800 gpm flowing through the drill pipe and 300 gpm flowing down a riser booster pipe.

A theoretical *Idealized Flat* system, where the fluid viscosities are held constant throughout the simulation, was compared to the Flat and Conventional field fluids. This idealized flat system is used to show a theoretical best case for a "flat rheology" system. **Tables 2 through 4** contain the fluid viscometer dial readings for evaluated systems.

Note in Table 4 the low shear rate viscosity tends to increase with temperature and pressure until the polymers lose effectiveness between 200^0 and 250^0F. This trend is the result of rheological property modifiers reacting with clay and solids and the ultimate loss of viscosity with increased temperature.

Figure 13 shows the effective viscosity (μ_{eff}) of each fluid with depth and the shear rates with the conditions listed above. Figure 14 shows the ECD profile for an *Idealized Flat* system compared to Flat and Conventional field systems. This example indicates the importance of understanding the temperature profile and the effect of pressure and temperature on the viscosity of the fluid. Pressure losses are a function of effective viscosity. Therefore, when comparing fluids for pressure loss characteristics under identical conditions, the fluid with the higher effective viscosity in the annulus will have higher pressure losses resulting in higher ECD.

When comparing the *Idealized Flat* to the Conventional system, the low shear rate in the riser contributes to the Conventional system having a lower effective viscosity. This results in the Conventional system exhibiting a lower ECD to about 11,800 ft. At around 11,800 ft, the ECD curves cross and the Conventional system has approximately 0.1 lb/gal higher ECD at 16,000 ft compared to the *Idealized Flat* fluid. This occurs because the Conventional fluid exhibits a higher effective viscosity in the casing and open hole.

The effective viscosity of the Conventional field system, compared to the Flat field system, is lower until about 11,500 ft. The significantly higher effective viscosity in the riser and marginal differences in effective viscosity in the open hole and casing of Flat system result in a 0.16 lb/gal higher ECD at TD, when compared to the Conventional system.

Problems using Bingham YP as an ECD Predictor

As discussed above, high shear rate viscosity, obtained from $511s^{-1}$ and $1{,}022s^{-1}$ shear rate readings, has little impact on annular pressure losses. The shear rates experienced in the annulus are significantly lower than these shear rates which are used to derive the Bingham YP.

Figure 15 illustrates the effective shear rates experienced by the fluids investigated in the above scenario. These low shear rates are typical for most deepwater wells due to large hole and casing diameters.

For most drilling scenarios, considerations for ECD management are best described by the 100 to 3 rpm oil field viscometer viscosities, measured under down hole temperature and pressure conditions. Further evidence of this is illustrated by revisiting Figure 14 and comparing with the results in **Figure 16**, where the calculated ECD's are almost identical. The ECD calculations were performed using the same viscometer measurements as used in Figure 14. The exception being the curves shown in Figure 16 were generated using only the 100 rpm, 6 rpm and 3 rpm values from each pressure and temperature data set (Tables 2, 3 and 4, yellow columns). By eliminating the 600, 300 and 200 rpm dial reading values from the viscometer data; the overall impact on ECD prediction is negligible. This result is not surprising since the shear rates and effective viscosity in the annulus are equivalent to those from an oil field viscometer between 100 and 3 rpm.

Conclusions

- Pressure loss models indicate an idealized Flat system will result in minimal ECD in deep water applications. In practice, it is difficult to maintain a flat effective viscosity profile with the effects of temperature, pressure, various base oils, rheological property modifiers, drill solids, and changing shear rate.
- The down hole pressure and temperature profiles should be used to optimize the drilling fluid's viscosity profile to plan and execute a successful drilling project. Surface pressure viscometer readings, should not be used to describe Flat YP systems and do not represent down hole behavior of any emulsion-based system.
- Flat systems use rheological property modifiers which have a tendency to develop high gel strengths that may help suspension of weighting material and cuttings under "static" conditions in a vertical well, but may lead to excessive down hole pressures.
- To achieve a Flat system with a flat yield point, the fluid viscosities are higher than a Conventional system in many circumstances.
- Conventional deep water drilling fluids inherently exhibit flat yield points above approximately 75°F under most drilling conditions. It is only at very low temperatures that the yield points vary significantly in value. The yield point of the Conventional systems tend to be lower than those of Flat systems under down hole conditions.
- A flat YP curve is not a predictor of ECD. Shear rates encountered in the annulus of most drilling applications are equivalent to oil field viscometer speeds of approximately 100 rpm to 3 rpm, not the 600 and 300 rpm used to extrapolate the YP.
- There are grounds for concerns that Flat systems have temperature limits between 200°F and 250°F, manifested by a drop in the YP, 6 rpm and 3 rpm dial readings and increased HPHT filtration rate.

Acknowledgments

The authors would like to thank Baker Hughes Drilling Fluids for granting permission to publish this paper.

Nomenclature

Conventional = conventional deepwater drilling fluid
ECD = equivalent circulation density
ESD = equivalent static density
Flat = flat yield point drilling fluid
gpm = gallons per minute
ROP = rate of penetration
RPM = revolutions per minute
SBM = synthetic based mud
SWR = synthetic water ratio
TD = total depth
TVD = true vertical depth
WOB = weight on bit

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Table 1: Components of synthetic based drilling fluids

TYPICAL COMPONENTS IN SYNTHETIC BASED FLUIDS	"FLAT"	Conventional
BASE SYNTHETIC	X	X
Weight Material	X	X
$CaCl_2$ Brine	X	X
Lime	X	low
Primary Emulsifier	X	X
Secondary Emulsifier	X	
Fluid loss control material	X	
Organophilic clay 1	low	X
Organophilic clay 2	low	
Bridging Material	X	X
Polymeric Rheology Modifier	X	
Thickening agent	X	
Dispersant/Conditioner	X	

Table 2: CONVENTIONAL down hole pressure / temperature viscometer readings

Conventional									
Temp, °F	Press, psi	600rpm	300rpm	200rpm	100rpm	6rpm	3rpm	PV, cP	YP, lbf/100ft^2
40	15	204	113	79	43	8	7	91	22
40	2500	262	146	98	63	14	12	116	30
40	5000	320	176	123	88	18	16	144	32
80	15	107	59	42	24	6	5	48	11
80	4600	153	88	63	39	8	7	65	23
100	6500	117	66	53	35	7	7	51	15
115	9100	130	73	55	37	8	7	57	16
120	10400	148	82	60	41	8	8	66	16
130	11700	144	80	59	40	8	7	64	16
135	12300	147	81	60	40	8	7	66	15
140	13100	150	83	62	41	8	7	67	16

Table 3: Idealized Flat Properties used ECD Simulations

Temperature, °F	Pressure, psi	600rpm	300rpm	200rpm	100rpm	6rpm	3rpm	PV, cP	YP, $lb_f/100ft^2$
All	All	95	61	48	34	19	18	34	27

Table 4: FLAT down hole pressure / temperature viscometer readings

Flat									
Temp, °F	Press, psi	600rpm	300rpm	200rpm	100rpm	6rpm	3rpm	PV, cP	YP, lbf/100ft^2
40	15	119	77	59	41	17	16	42	35
40	2500	153	101	79	55	23	21	52	49
40	5000	188	119	93	64	26	24	69	50
75	15	79	50	40	29	14	14	29	21
75	5000	131	86	69	49	24	23	45	41
100	5300	105	72	59	44	25	25	33	39
115	9000	118	81	66	49	28	27	37	44
120	10300	119	82	67	50	29	29	37	45
130	11600	121	83	68	51	30	29	38	45
135	12200	122	84	69	52	31	30	38	46
140	12900	123	85	69	53	22	31	38	47
200	15000	99	70	58	46	31	30	29	41
250	17500	70	39	30	20	9	9	31	8

Figure 1: Kinematic viscosity of synthetic base fluids

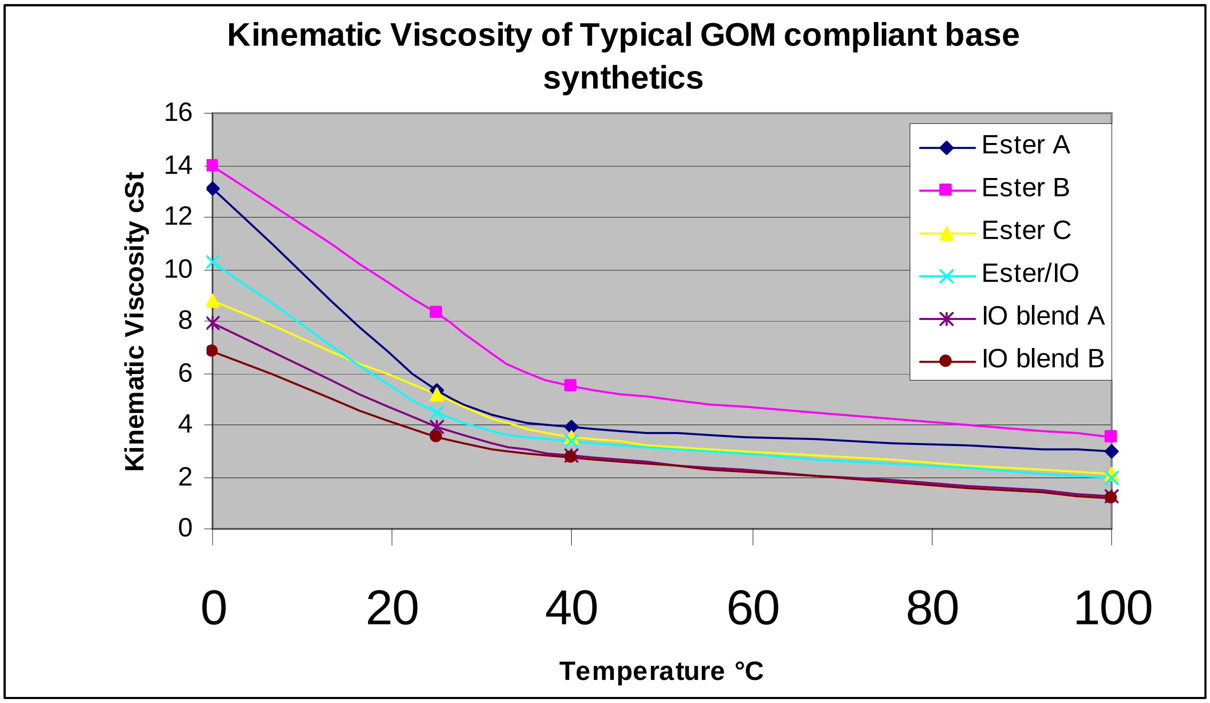
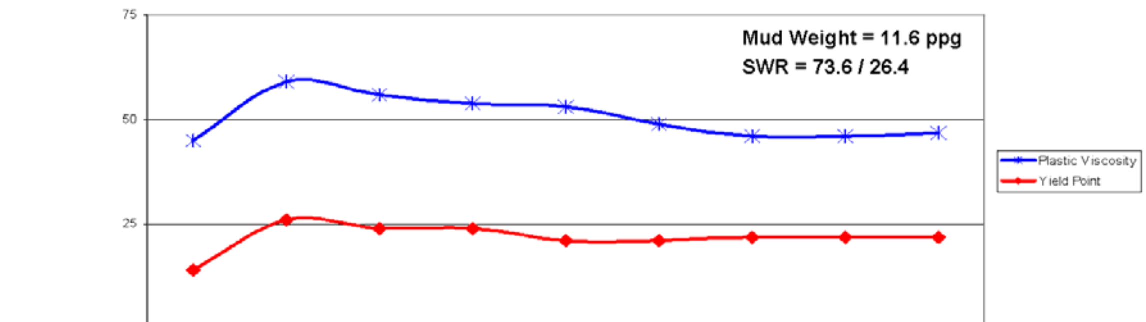
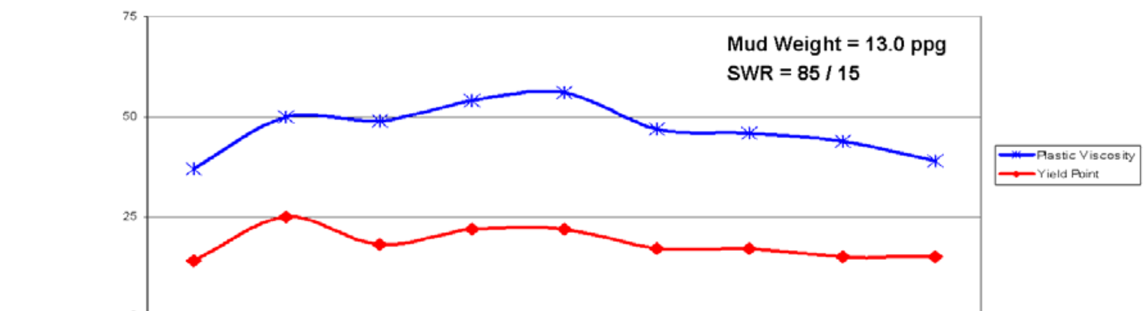


Figure 2: Conventional Systems YP and PV under Pressure and Temperature



	1	2	3	4	5	6	7	8	9
Temp, F	75	75	90	95	100	105	115	118	125
Pressure, psi	14,5	3436	4541	5213	5518	6026	7040	7530	8088
Plastic Viscosity	45	59	56	54	53	49	46	46	47
Yield Point	14	26	24	24	21	21	22	22	22



	1	2	3	4	5	6	7	8	9
Temp, F	75	70	75	80	85	100	115	125	130
Pressure, psi	14,5	1352	2366	5070	5746	7571	8247	8923	9667
Plastic Viscosity	37	50	49	54	56	47	46	44	39
Yield Point	14	25	18	22	22	17	17	15	15

Figure 3: Temperature effect on HPHT fluid loss in Flat and Conventional field systems

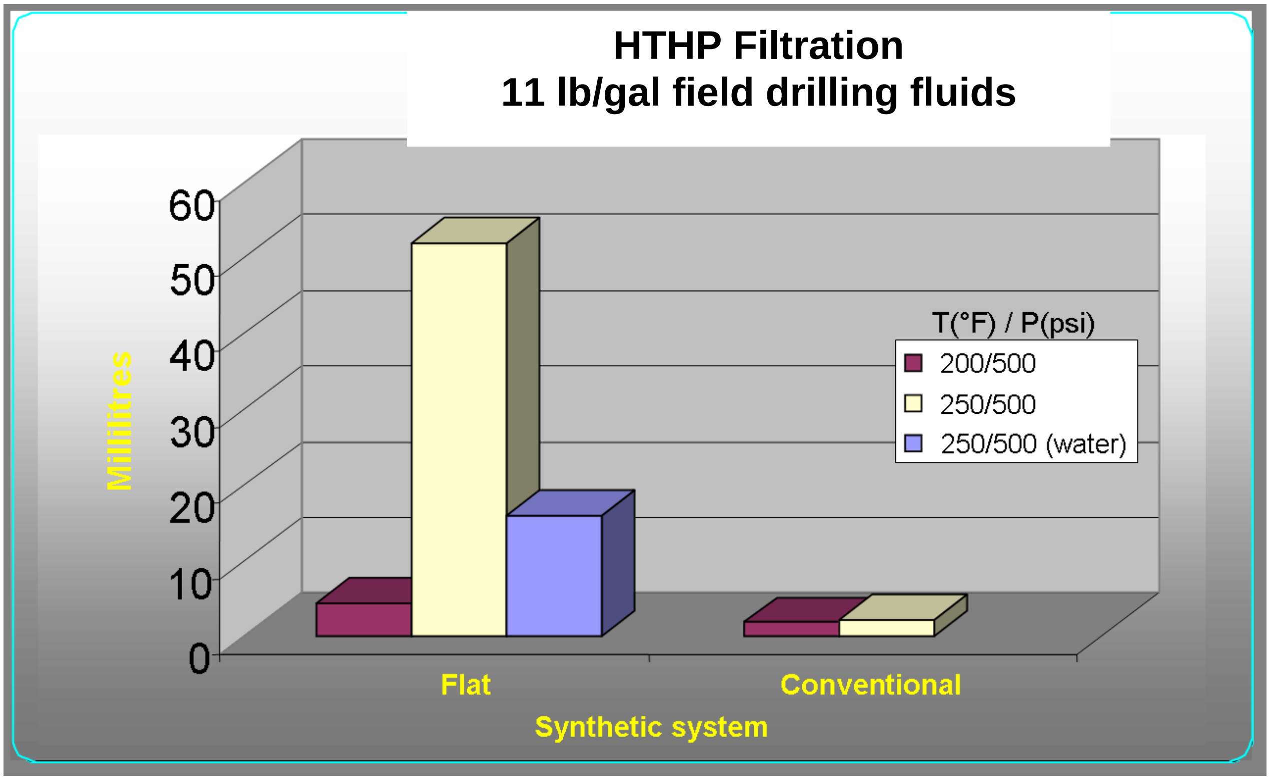


Figure 4: Rheological property modifier concentration effects on Flat Systems

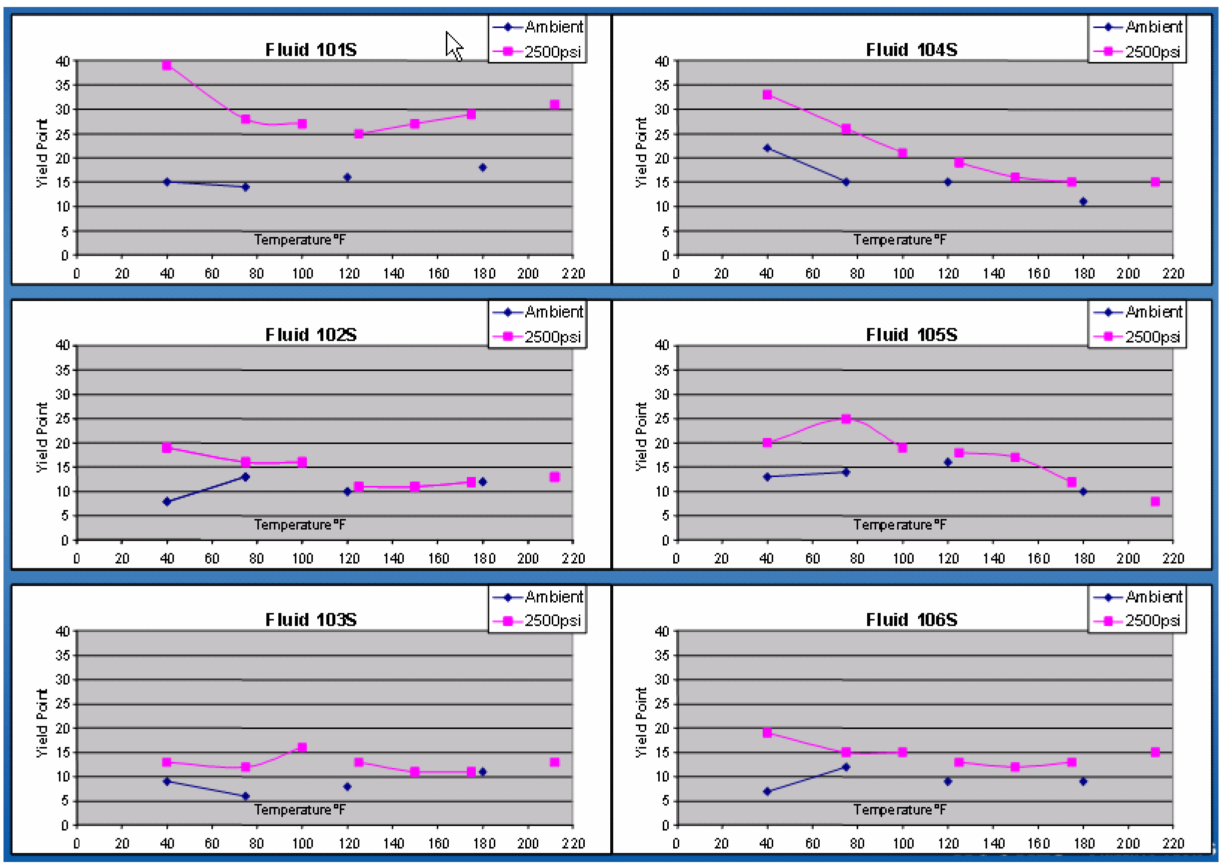


Figure 5: Lime concentration effects on YP of Flat field system

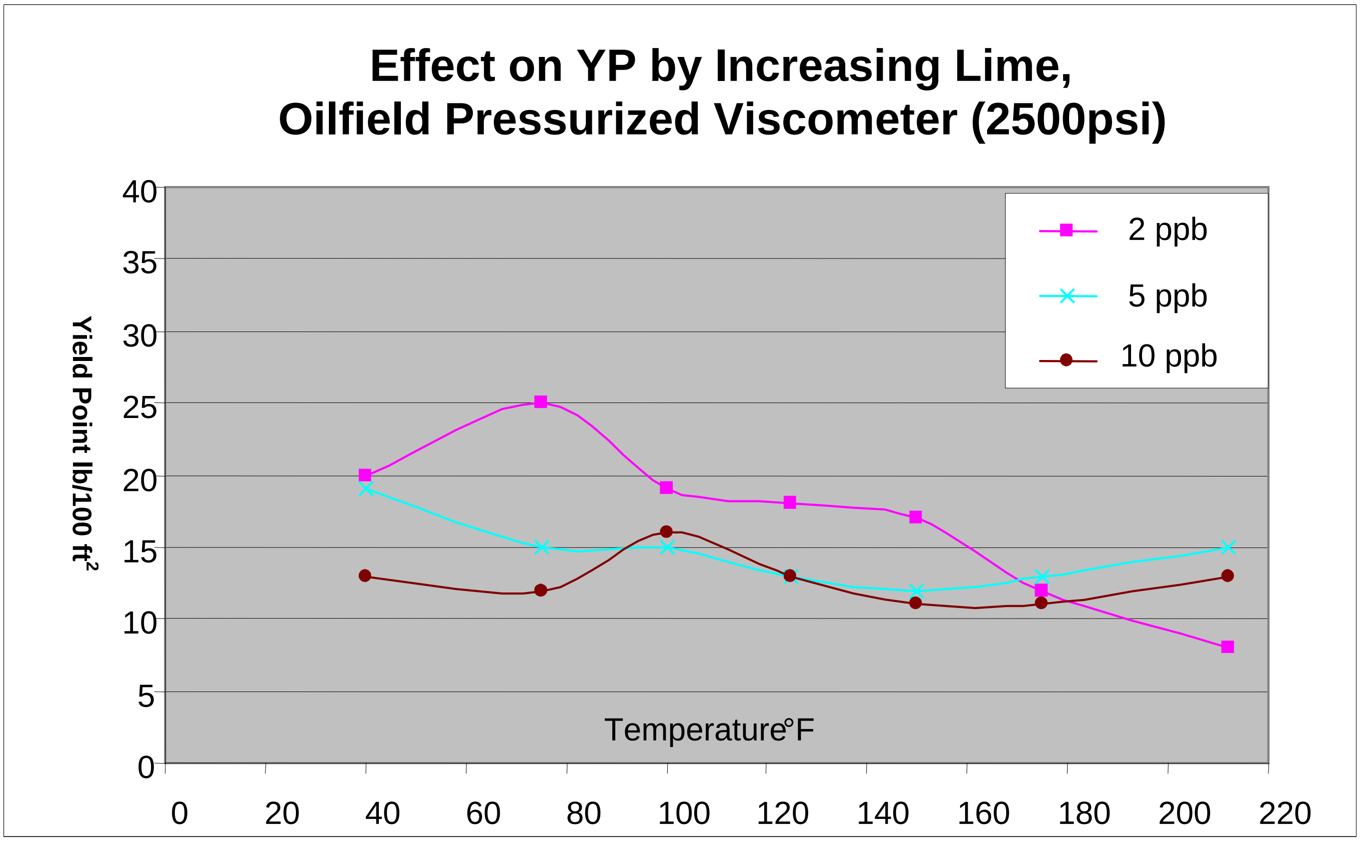


Figure 6: Temperature effect on YP at surface pressure

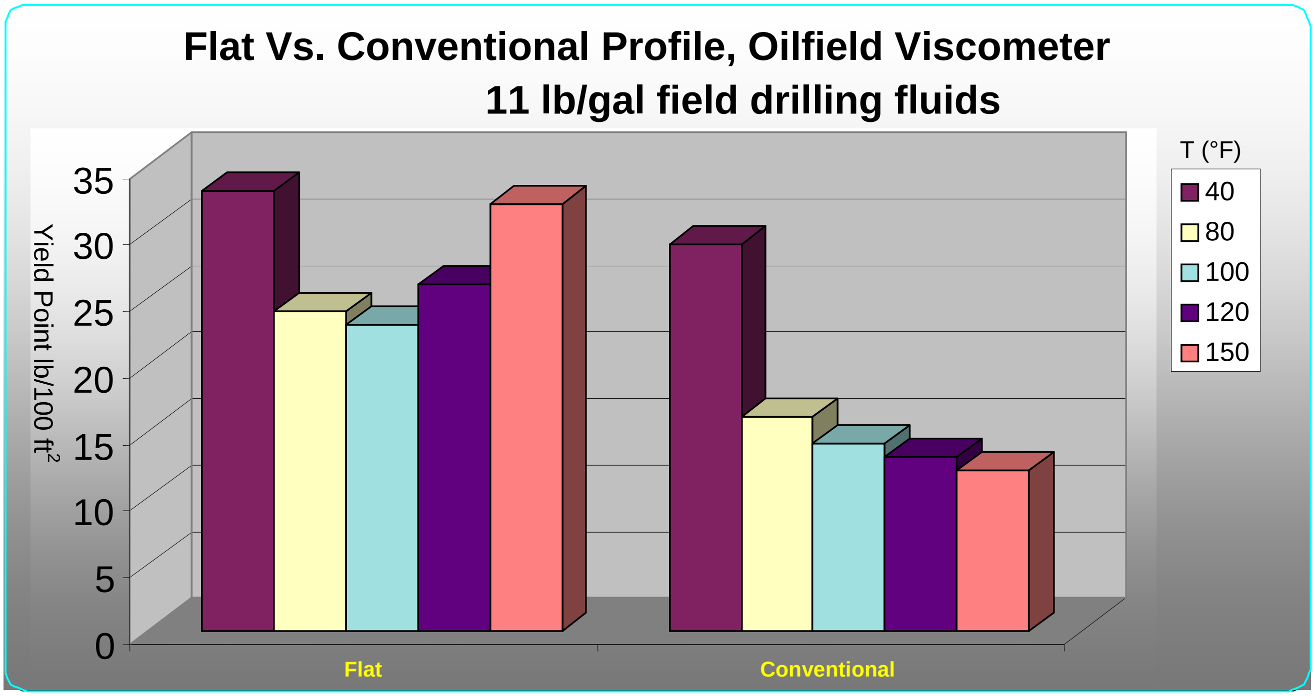


Figure 7: Temperature/Pressure effect on YP

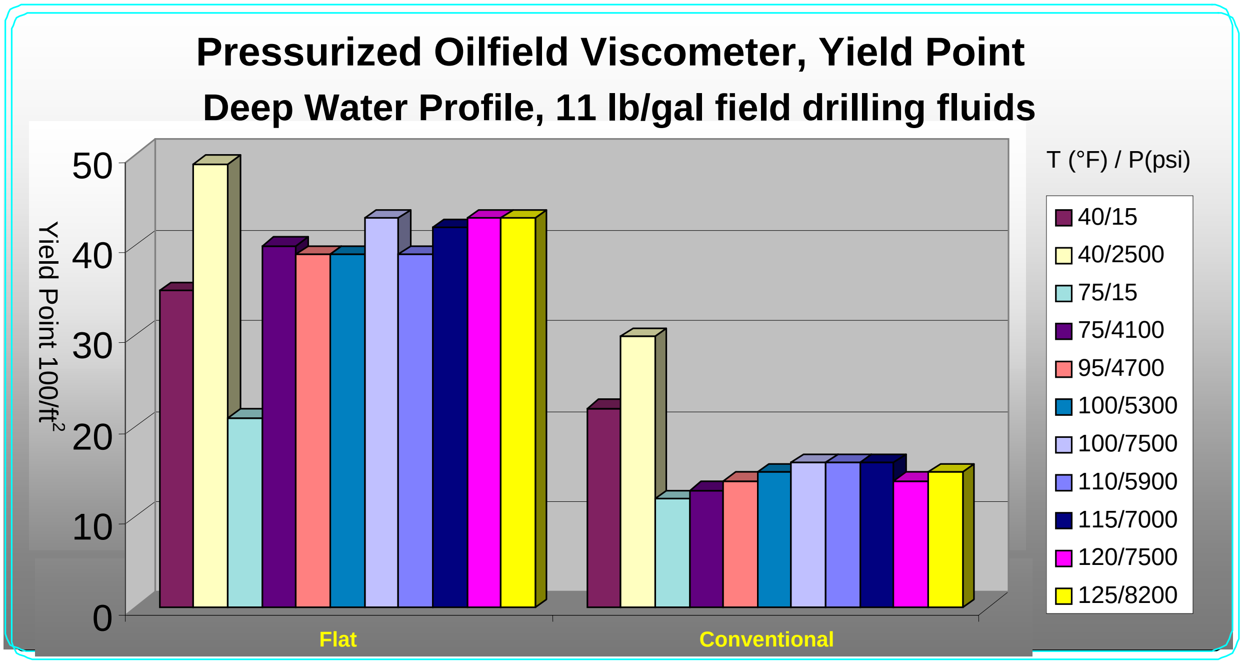


Figure 8: Measured at 120°F and surface pressure

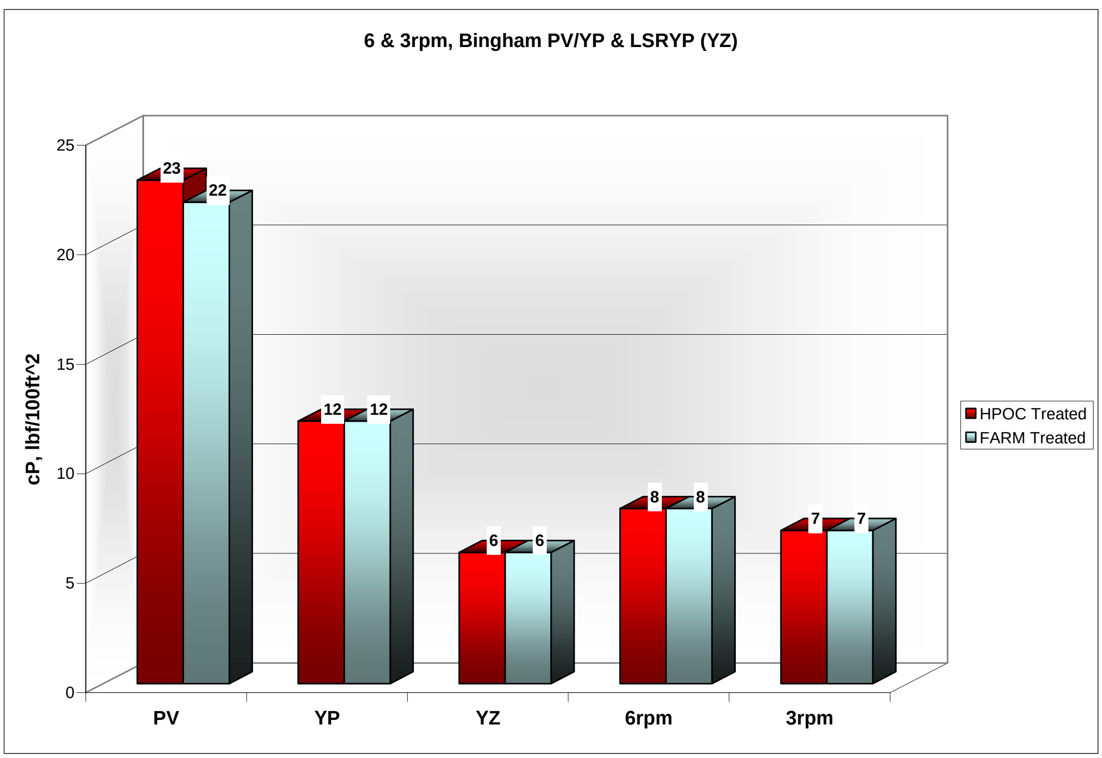


Figure 9: Measured under Down Hole conditions

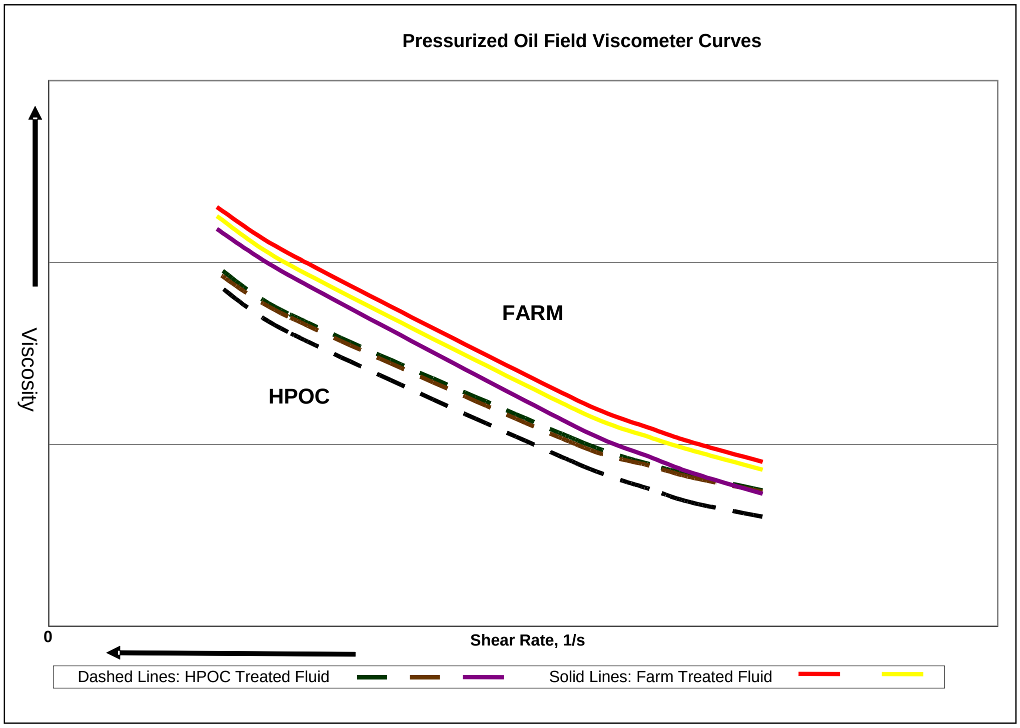


Figure 10: Example - Effect of Oil Type on Density with Temperature and Pressure

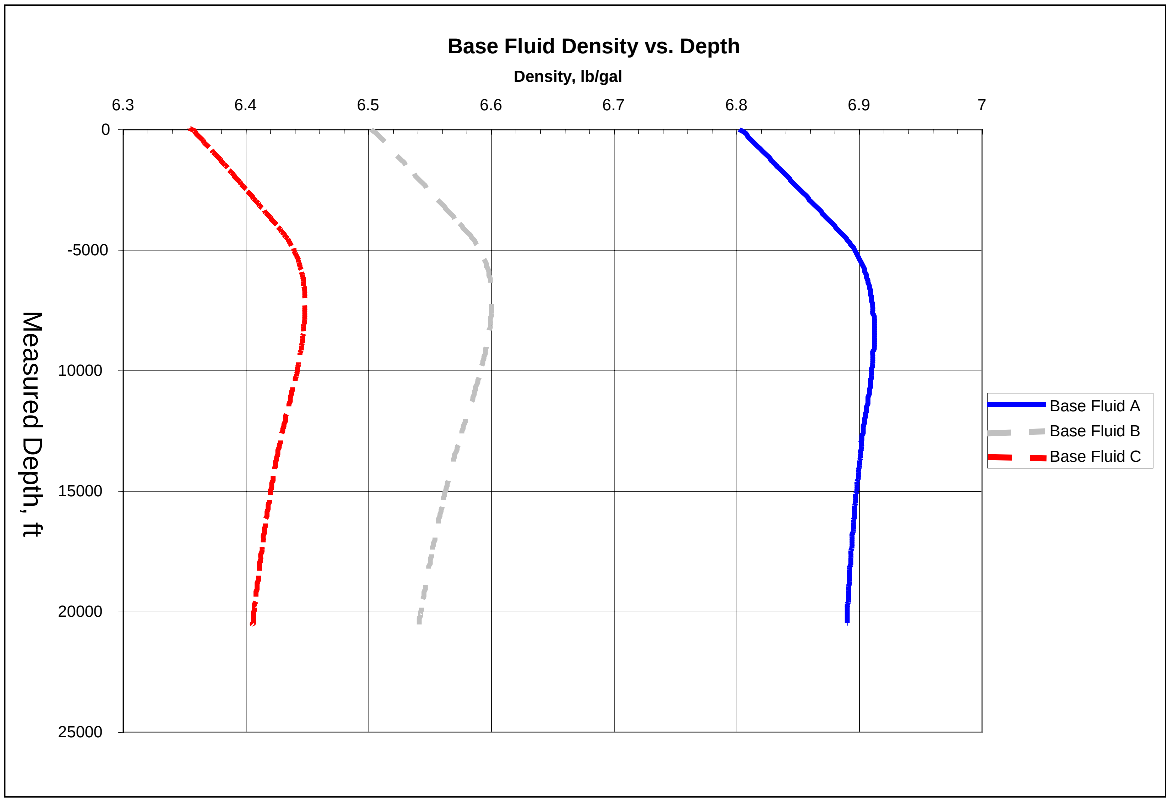


Figure 11: Example Effect of Temperature and Pressure on Oil Density

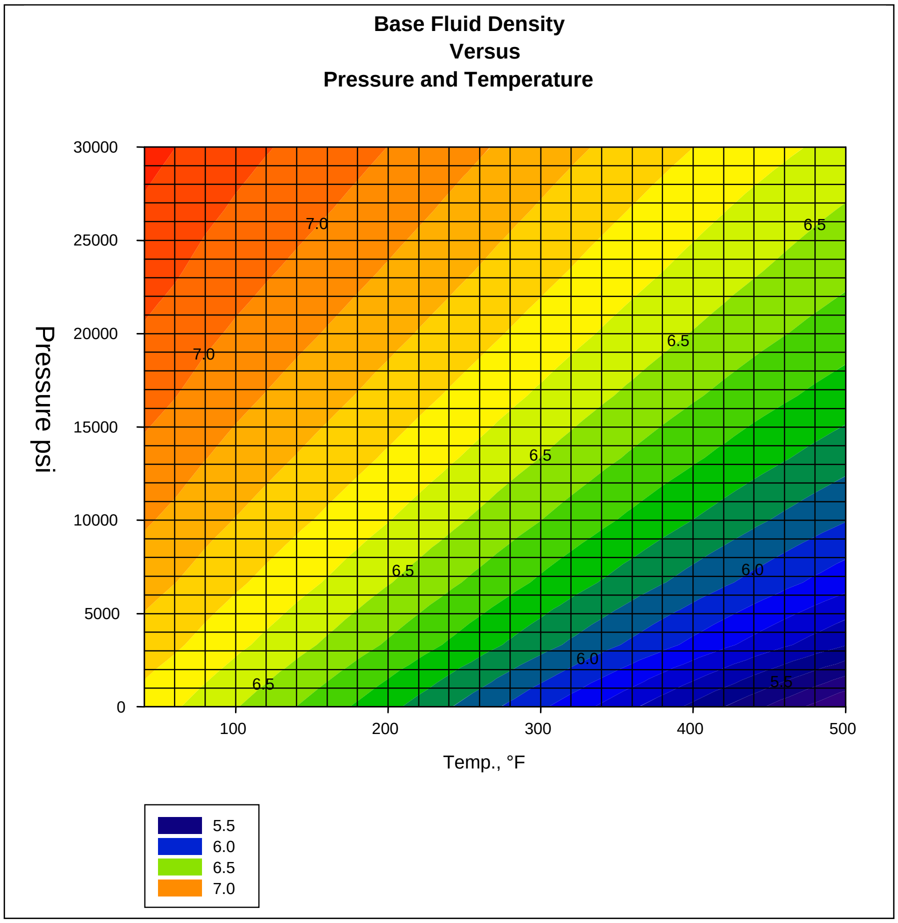


Figure 12: Newtonian / non-Newtonian viscosity profile

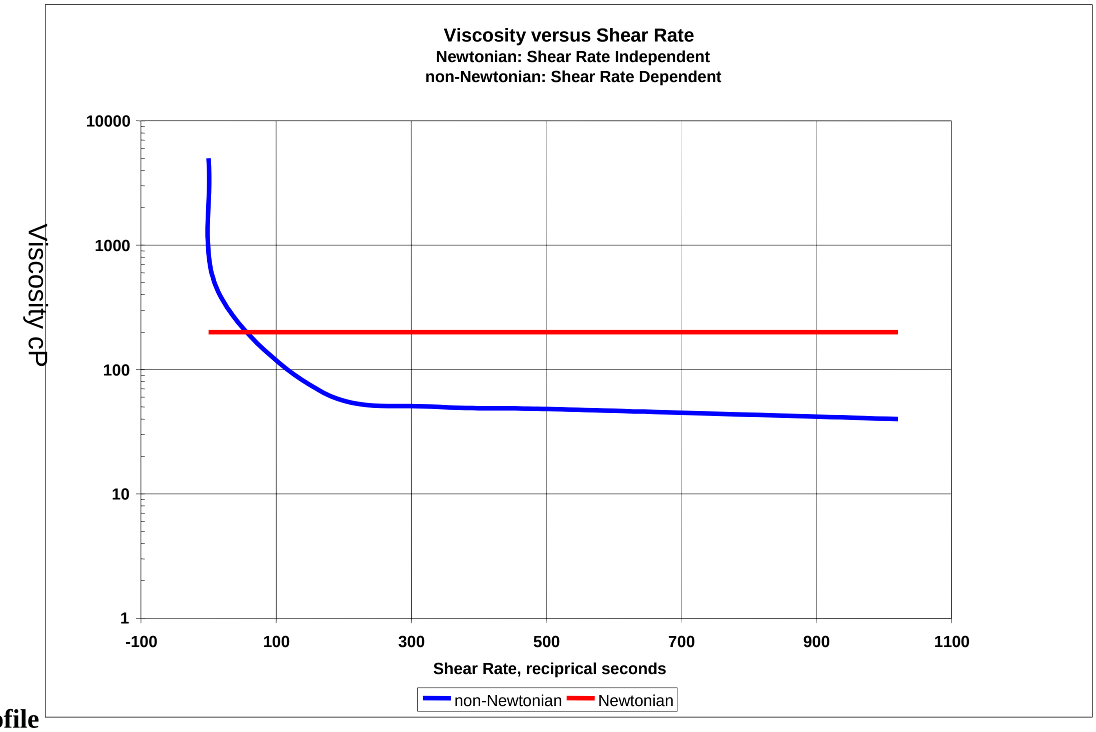


Figure 13: Best Case - 7400 feet of 19.5" riser 16,000 ft
Idealized Flat, Flat and Conventional systems effective viscosity

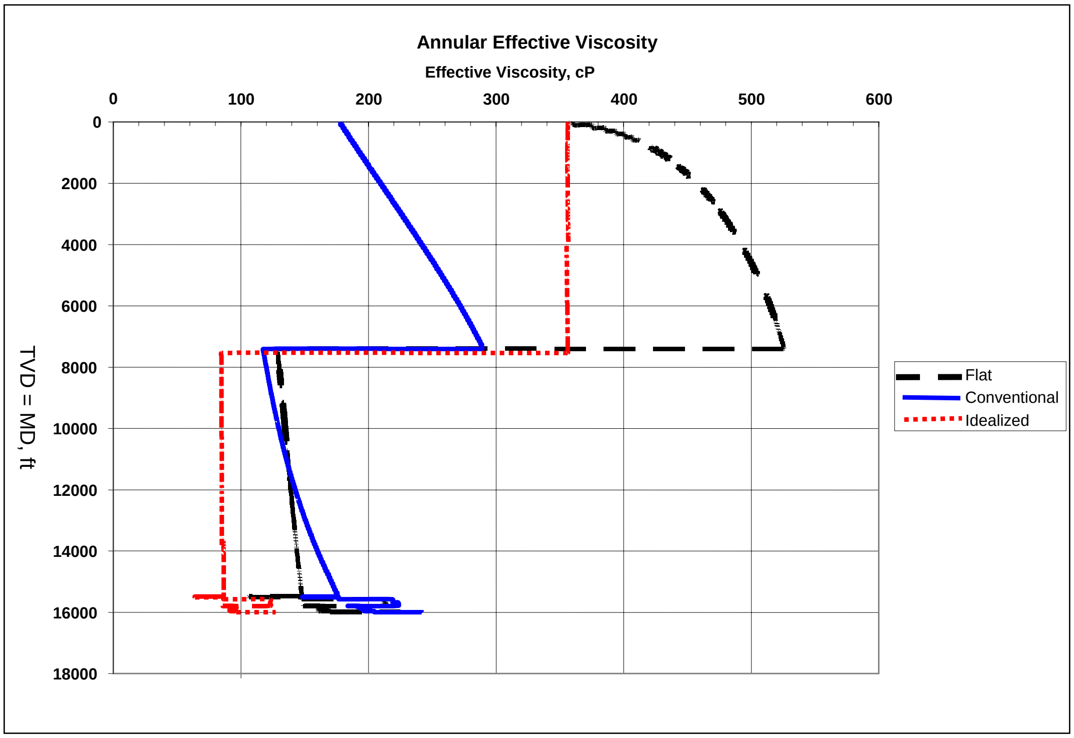


Figure 14: Best Case - 7400 feet of 19.5" riser 16,000 ft
Idealized Flat, Flat and Conventional System ECD with depth

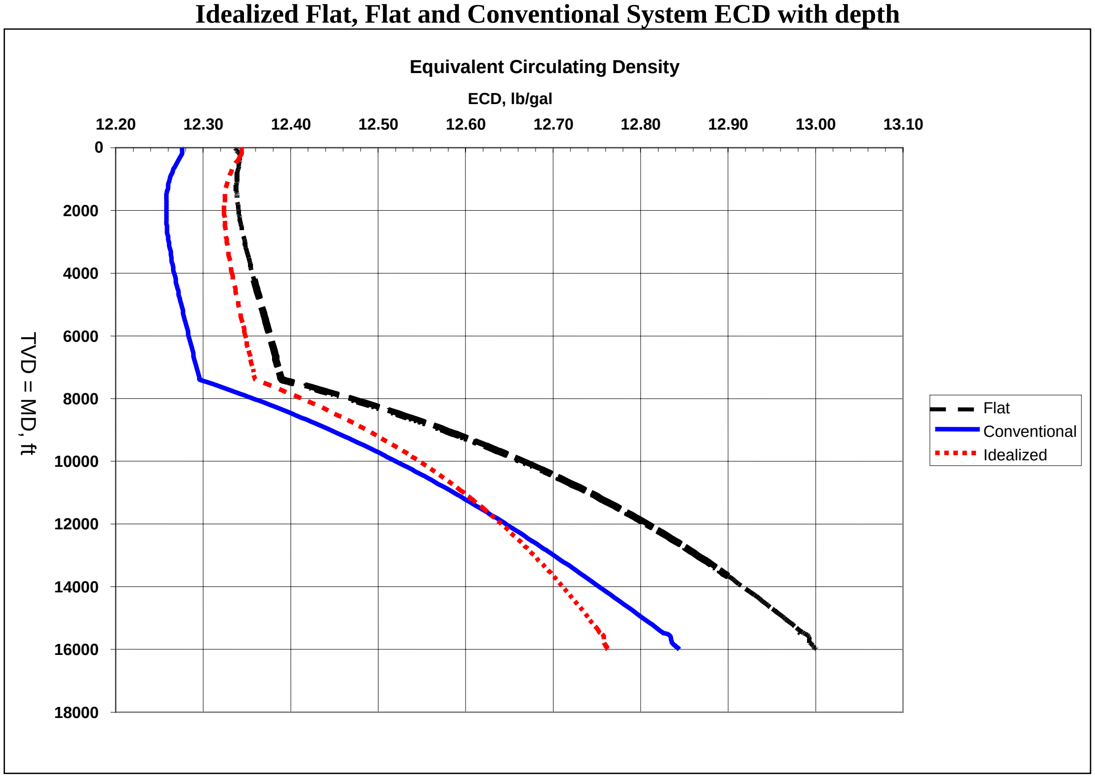


Figure 15: Best Case - 7400 feet of 19.5" riser 16,000 ft Typical annular shear rates

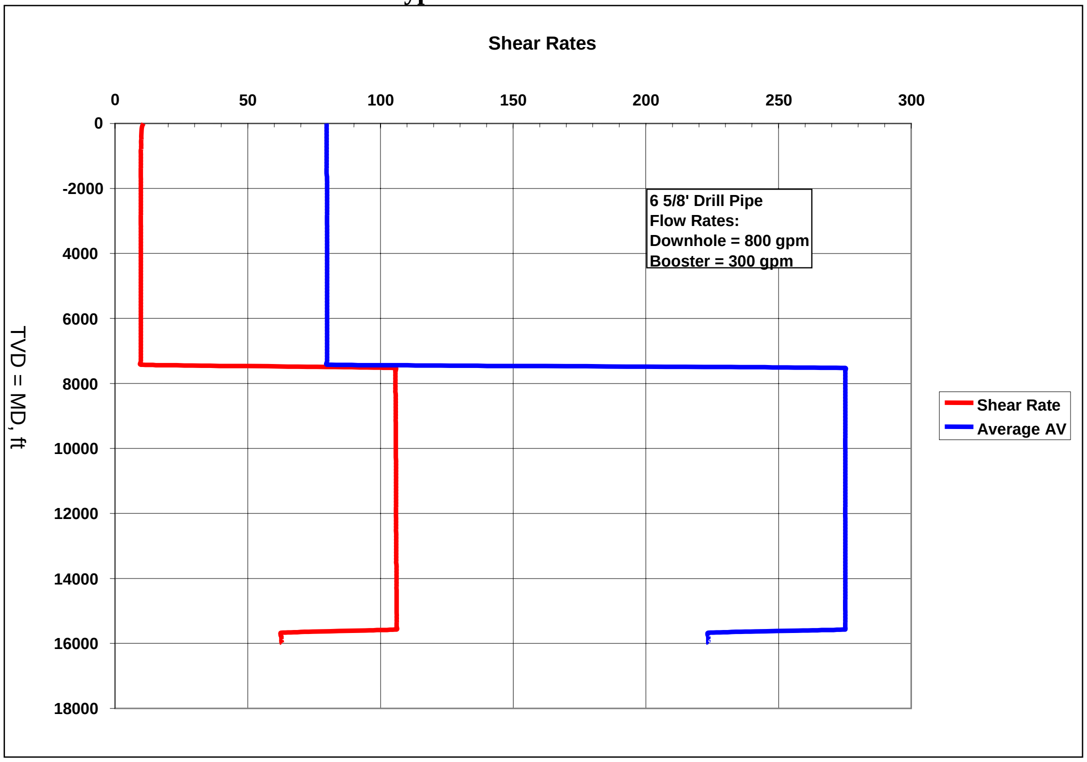


Figure 16: Best Case - 7400 feet of 19.5" riser 16,000 ft Idealized Flat, Flat, and Conventional Systems ECD calculated using only 100-3 rpm readings