

Investigation on the Effects of Ultra-High Pressure and Temperature on the Rheological Properties of Oil-based Drilling Fluids

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Abstract

The extreme high pressure, high temperature (XHP/HT) environment associated with Deep Shelf drilling in the Gulf of Mexico and the deviated HP/HT wells drilled in the North Sea require the development of stable drilling fluid formulations. A major cause of problems is the thermal degradation of chemical additives often used in drilling fluid formulations. Such thermal degradation can lead to strong variations in rheological and filtration characteristics and loss of properties. Moreover, even if no degradation of components occurs, the viscosity of hydrosoluble polymer solutions commonly used in fluid formulations strongly decreases as temperature increases above 150°F.

Secondly under extreme wellbore pressure conditions, only a small hydrostatic overbalance can be tolerated due to the reduced margin between pore and fracture gradients. Therefore it is vital that both the hydrostatic overbalance and the dynamic pressures are accurately modeled and managed, otherwise, losses may result. Thus, the effects of pressure on a drilling fluid's viscosity under downhole conditions and on the equivalent circulating density (ECD) cannot be ignored.

To fully investigate the main and interaction effects of ultra-high pressure and temperature on the rheology of oil-based fluids several laboratory experiments were performed. Both diesel and mineral oil-based fluid types were tested to 600°F and 40,000 psig using a new generation XHP/HT viscometer. Results show that the nature of the constituents used in the fluid formulation strongly influences the fluid's behavior under these harsh conditions. Thermal degradation causes permanent changes in a fluid's composition leading to abnormalities in its rheological response.

Introduction

Generally a drilling fluid experiences two opposing effects as the temperature and pressure in the wellbore increases with depth. Increase in pressure increases the fluid's viscosity due to its compressibility, whereas the increase in temperature increases the random motion of the macromolecules dissolved in the fluid matrix. As a consequence, there is reduced molecular interaction and hence reduced viscosity. However for a particular temperature and pressure profile, these two opposing effects may cancel out, resulting in a uniform fluid viscosity / density along the depth of the well that is equal to

that at surface. The general practice is to measure a fluid's flow characteristics under ambient surface conditions and extrapolate these measurements in some way to the down hole conditions. This requires a reliable model of how the rheology of the fluid changes with the cyclical variations in temperature, pressure and shear history which it experiences during circulation inside the wellbore. Despite a considerable experimental study over the years, for both water- and oil-based fluids, there is relatively little systematic understanding of how their flow behavior changes with down hole conditions for the following reasons¹:

1. It has been common practice to make measurements of shear rheology at relatively few shear rates and to represent shear stress/shear rate curves (rheograms) by simple two-parameter constitutive models, such as the Bingham Plastic or Power Law models which are not adequate especially in HP/HT situations.
2. The rheology of the fluid is influenced by many factors including temperature, pressure, shear history, composition and the electrochemical character of the components and of the continuous fluid phase. These effects can be summarized as follows:

Physical effects: Decreases in temperature and increases in pressure both affect the mobility of the systems and lead to an increase of apparent viscosities and visco-elastic relaxation times. The effect of pressure is expected to be greater with oil based systems owing to the oil phase compressibility.

Electrochemical effects: An increase in temperature augments the ionic activity of any electrolyte, and the solubility of any partially soluble salt that may be present in the fluid. This could alter the balance between the inter-particle attractive and repulsive forces and so the degree of dispersion and flocculation of the mud systems.

Chemical effects: At temperatures above 200°F all hydroxides react with clay minerals. With many mud systems, this can result in a change of the structure and therefore also in a change of the mud rheological properties.

The temperature at the bottom of the hole increases as the depth of the well increases. Naturally, the drilling fluid

temperature will approach the geothermal gradient when it is not being circulated during a trip or on logging runs. However the temperature of the fluid is always in a transient state strongly sensitive to the flow rate as presented by Karstad and Aadnoy². Recent advances in temperature modeling have led to a better understanding and development of some brilliant interpretation techniques. A drilling fluid's viscosity is directly related to the downhole variations in pressure and temperature and is a very important part of drilling engineering.

Oil-based drilling fluids have some advantages when compared to water based fluids in XHP/HT applications. These include maintaining stable rheology and filtration control for extended periods of time and increased lubricity. In addition, oil base drilling fluids can be used to drill through most troublesome shale formations due to their inherent inhibitive nature and temperature stability. However, most commercial oil base drilling fluid systems have limitations such as reduced rheology and filtration control when exposed to temperatures higher than 300°F for prolonged periods of time. Also there is the issue of hydrogen sulfide and methane absorption.

In XHP/HT wells, only a small hydrostatic overbalance can be tolerated due to the reduced margin between pore and fracture gradients, Therefore it is vital that both the hydrostatic overbalance and the dynamic pressures are adequately managed, otherwise losses or influx may result. This paper presents results of extensive laboratory experiments on oil-based drilling fluids. Several experiments were performed using oil-based drilling fluids in order to understand the recipe effects on mud behavior at pressure and temperature.

Fluid Samples

Throughout the course of this research emphasis was placed on proper fluid preparation and sampling as this could result in significant discrepancies given that all the oil-based fluids used are solids laden and hence easily susceptible to sag. Two different oil-based fluid formulations were used during this research. For confidentiality they will be referred to as "Fluid Type A" and "Fluid Type B". Below is a brief description of the fluids.

Fluid Type A: This was the first fluid formulation to be used in this research. The base oil was diesel and it was weighted with barite. The original fluid was obtained from the field and then improved in the lab with some additives. The fluid had a density of 18.8 ppg and an oil/water ratio of 91/9.

Fluid Type B: This fluid was used extensively in this research. It is a mineral oil based fluid with a mud density of 18.0 ppg and 93/7 oil/water ratio. Average Electrical Stability (ES) was 950. Two formulations have been used B1 and B2. The difference between B1 and B2 consists of the additives used to enhance the thermal stability.

Fluid Preparation

Before testing the fluid with the XHP/HT viscometer these steps are followed:

1. The whole fluid in the bucket is stirred first with a paddle then with two Hamilton Beach mixers at 70 RPM for less than 5 minutes to ensure a homogeneous mixture.
2. A sample (usually 2 lab barrels) is then poured out into a cup and uniformly sheared at low speed in the Hamilton Beach mixer for 10 minutes. After collecting the sample the remaining fluid in the bucket is properly covered to avoid contamination.
3. Using a syringe 25 ml is extracted and 175 ml poured into the test cell of the XHP/HT viscometer.
4. The remaining was poured into the thermo-cup for initial rheology check with the Fann 35.

Experiments

The laboratory experiments conducted during this project can be broadly classified into two: baseline and factorial experiments. For each experiment, the initial rheology check was performed at 150°F and ambient pressure (14.7 psia) using both the XHP/HT and Fann 35 viscometers. Using two or more viscometers was necessary for better quality control and to ensure consistency in results.

Baseline Experiments

For these experiments, the temperature and pressure of the fluid sample was simultaneously increased from 150 to 600°F and 0 to 40,000 psig respectively. The schedule for these tests were designed by increasing temperature by 50°F from 150 to 400°F and then by 25 to 600°F. Pressure increments ranged from 3,000 to 5,000 psig. Viscosity measurements are taken at each increment. The baseline experiments replicate real-time conditions in typical Gulf of Mexico XHP/HT wells. To illustrate, the following baseline tests are presented.

Baseline Tests: Several baseline tests were carried-out using Fluid Type A. baseline Test 2 is a typical test run for temperatures between (150°F and 600°F) and pressures up to 40,000 psig while taking 600 to 3 RPM dial readings and gels strengths at intervals. Baseline Test No. 4 is similar to Baseline Test No.2 only that it is done at a constant 300 RPM (i.e. 511 sec⁻¹) shear rate. No other shear rate readings were taken. This test was done to investigate the effect of constant shear rate on the fluid's viscosity over time. **Figs 1 and 2** are plots of apparent viscosity versus temperature and pressure. In both plots temperature and pressure are increasing simultaneously.

The graph of Baseline Test 4 is similar to that of Baseline Test 2 with the viscosity increasing sharply at about 425°F; however the viscosity profile is slightly higher than that of Baseline Test 2.

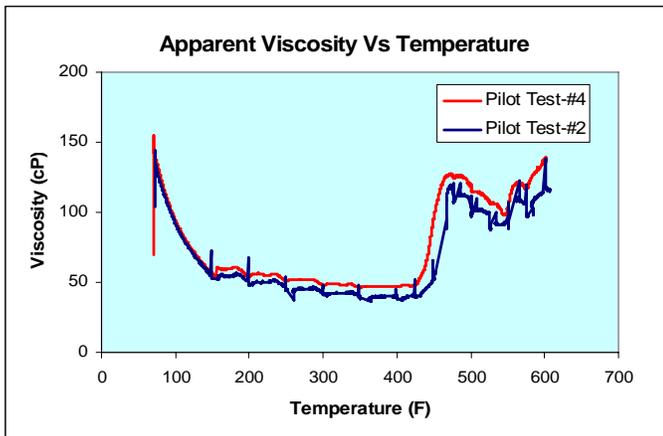


Fig. 1—Apparent viscosity vs temperature for baseline test 2 & 4

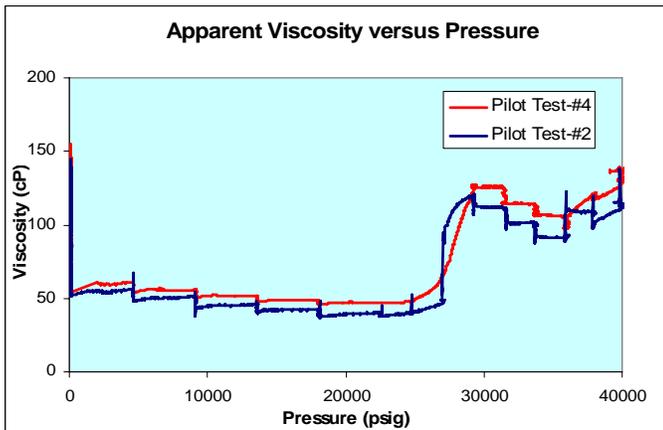


Fig. 2—Apparent viscosity vs pressure for baseline test 2 & 4

From the plots above, the general trend is the same with both tests breaking-out at 425°F. However notice that beyond 150°F the viscosity profile for Baseline Test 2 is lower than that of Baseline Test 4. Also the spikes in viscosity readings of Baseline Test 2 are due to the gel effect when revving back to 300RPM after each gel strength test.

Comparison Tests: Using Fluid Type B, two baseline tests were performed to investigate the effects of recipes (B1 and B2) on the thermal stability of the fluid. Both fluid formulations had a density of 18.9 ppg. The maximum temperature and pressure attained was 600°F and 33,000 psig. No gel strength readings were taken. Raw data have been withheld for confidentiality. **Figs. 3** and **4** show plots of plastic viscosity and yield point versus temperature. These were similar to the pressure plots.

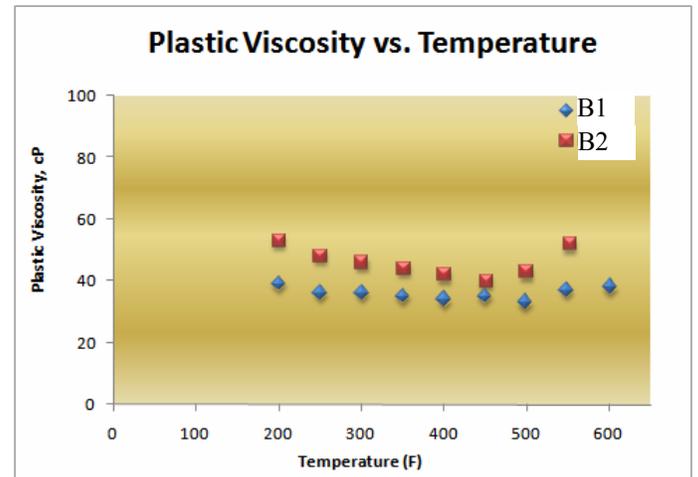


Fig. 3—Plastic viscosity vs. temperature for recipes B1 and B2

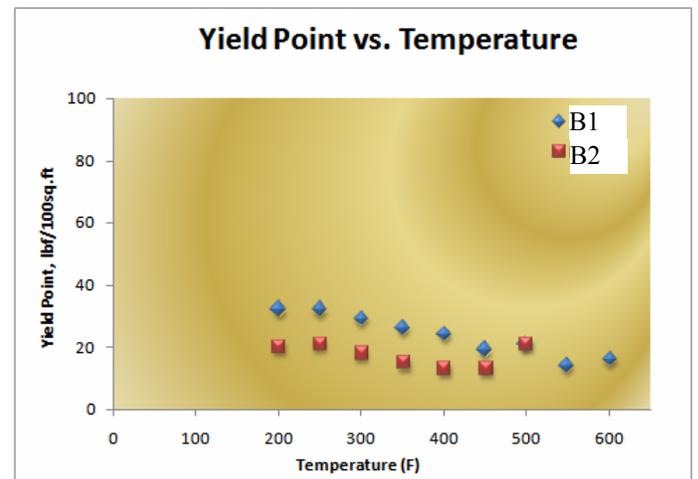


Fig. 4—Yield point versus temperature for recipes B1 and B2

In summary, the results of these tests showed that:

- For similar pressure and temperature conditions, the B1 formulation had lower plastic viscosity and yield strength values.
- The B1 formulation also had better thermal stability (up to 600°F) when compared with the B2 formulation which was only stable up to 450°F.

Two baseline tests were also performed using Fluid Type A with similar results.

Factorial Experiments

A factorial experiment consists of two or more factors, each with discrete possible values or "levels", and whose experimental units take on all possible combinations of these levels across all such factors. Such an experiment allows studying the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. Several factorial experiments were carried

out during this research. They are discussed under the following headings:

Constant Temperature, One-way Factorial Tests: The tests schedules for this phase involved keeping temperature constant while increasing pressure from 5,000 psig to 40,000 psig at increments of 5,000 psig. Viscosity measurements were taken at each pressure increment. No measurements were taken while releasing pressure from the test cell, hence the term one-way. **Figs 5 and 6** show the plastic viscosity and yield point plots for the 8 tests performed.

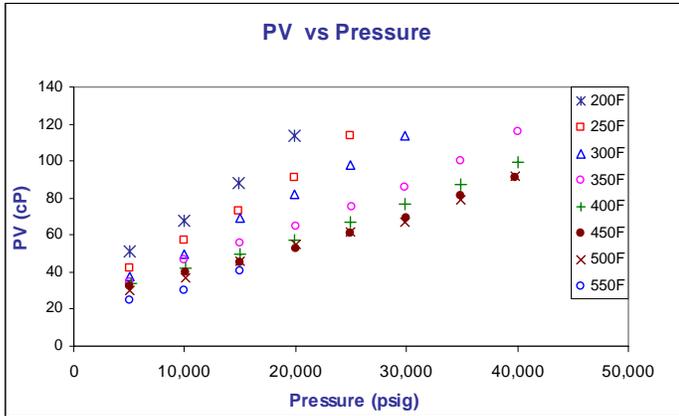


Fig. 5—Plastic viscosity (PV) versus pressure

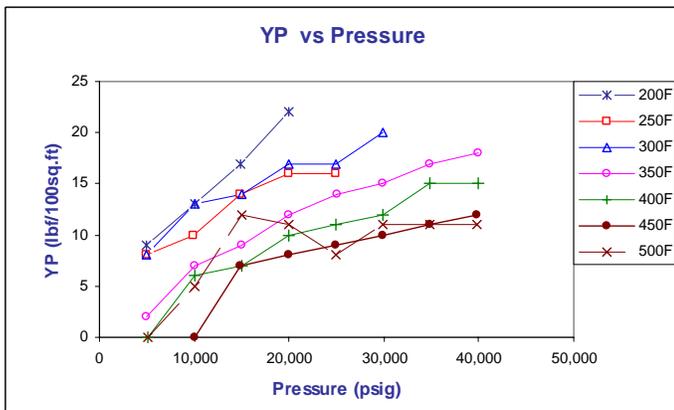


Fig. 6—Yield point (YP) versus pressure

The observations made above are true for the plastic viscosity plot. The yield point values are less uniform but they generally increase with increasing pressure or decreasing temperature.

Constant Pressure, One-way Factorial Tests: This time pressure was kept constant while increasing temperature from 150°F to 600°F starting with the first test at constant 5000 psig. Nominal 50°F temperature increments are used initially, however significant changes in viscosity warranted smaller increments (25°F) from 400°F to 600°F. There was a steady decline in viscosity with increase in temperature up to about 450°F, where there is a sharp increase due to thermal

degradation which caused a significant change in the composition of the fluid. This behavior was repeated for all the other tests in this sequence regardless of the set pressure. A total of eight (8) tests were performed in this phase like in the previous phase with an average of 6hrs per test using the XHP/HT viscometer. **Figs 7 and 8** are plots of plastic viscosity and yield point versus temperature respectively.

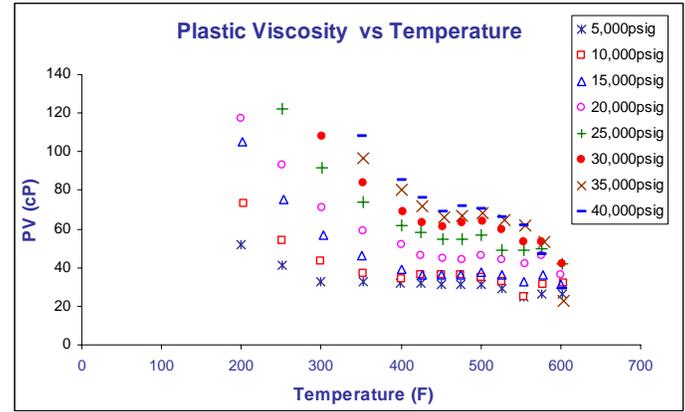


Fig. 7—Plastic viscosity versus temperature

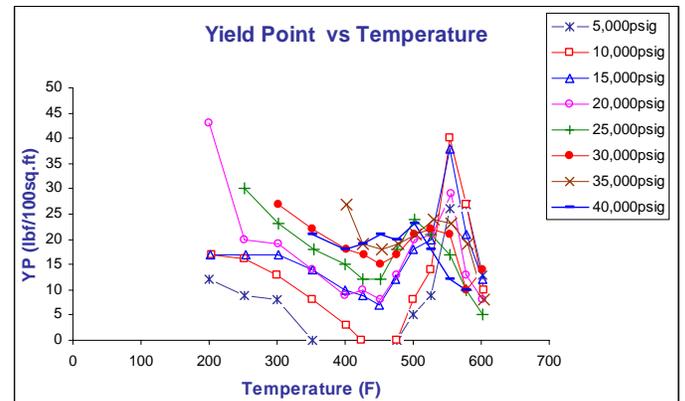


Fig. 8—Yield point versus temperature

The following observations can be made from the Figs 7 and 8 above:

- There is decline in viscosity with temperature until 450°F.
- Beyond 450°F there is a slight increase in viscosity, which levels at 500°F and then declines to 600°F. This is also true for yield point data in Fig. 8, the difference being the magnitude of the increase and decrease.
- All the data points tend to converge at 600°F. This indicates that irrespective of the prevailing pressure, the fluid behavior is essentially the same at 600°F. In other words, effect of pressure is strongest at low temperature.
- Yield point data for the 5,000 psig and 10,000 psig curves become negative between 350°F and 475°F so those sections have been omitted. This is unrealistic and suggests non-Bingham plastic behavior.

Constant Shear Rate and Pressure Two-way tests: Shear rate was maintained constant at 170sec⁻¹ (100 RPM)

representative of annular flow past the drill collars. All the test schedules for this phase were designed so that the 100 RPM readings could be taken while heating and again when cooling down hence the term “two-way”. **Fig. 9** below shows a combined plot (of 100 RPM dial readings versus temperature) for seven (7) tests.

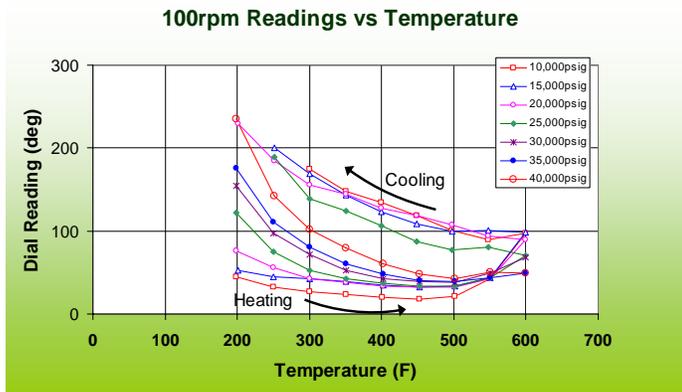


Fig. 9–100 RPM dial readings versus temperature

The following conclusions can be drawn from Fig. 9:

- At lower temperatures (<350°F), the effect of pressure is very noticeable from the spread in the “Heating” curves.
- The relationship between temperature and dial readings is exponential just as found earlier from the multiple shear rates, variable temperature and constant pressure tests.
- There is a general convergence of all the “Heating” curves at 550°F which then they deviate slightly at 600°F.
- The “Cooling” curves tend to align to each other regardless of pressure. This goes to indicate that the behavior of the thermally degraded fluid is essentially the same for the different pressure profiles.

Constant Shear Rate and Temperature Tests: Seven (7) tests were performed as plotted in **Fig 10**. Results of these tests are analogous to those of the multiple shear rates, variable pressure and constant temperature tests. As observed earlier, linear relationship exists between shear rate and pressure at constant temperature.

TX Test Series: The TX-1 to 4 series of tests were done to further investigate the behavior of the same Fluid Type B beyond 450°F at high shear rates (300 RPM and 600 RPM) and constant pressure of 10,000 psig. The test schedules for this series were designed so that initial readings can be taken while heating and repeat readings when cooling down like the two-way test discussed earlier. A total of eight (8) tests were carried out. One original and then a repeat for each test schedule. A brief description of the four tests as plotted in **Fig 11** is given below:

- TX-1: (300 RPM at max 600°F and 10,000 psig)
- TX-2: (300 RPM at max 450°F and 10,000 psig)
- TX-3: (600 RPM at max 450°F and 10,000 psig)
- TX-4: (600 RPM at max 600°F and 10,000 psig)

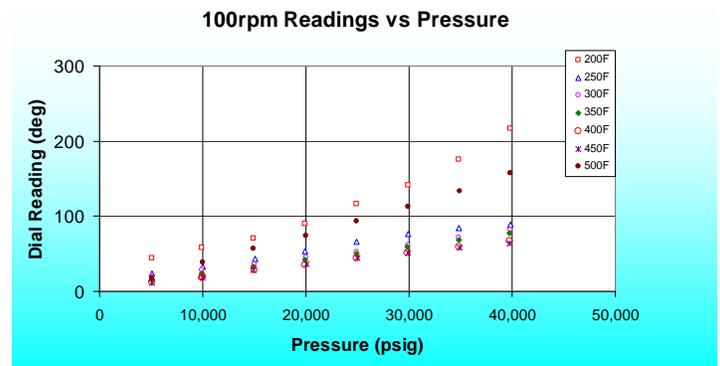


Fig. 10 –100 RPM dial readings versus pressure

The repeat experiments (**Fig 12**) were performed to ensure reproducibility of the original results. The plots are quite similar. The major difference is in the higher dial reading response of TX-4 repeat test. This could have been caused by fluid thickening with time as the TX-4 was the last to be done in the series. The initial rheology check involves measuring the 600, 300, 200, 100, 6, and 3 RPM readings and gel strengths at 10 seconds and 10 minutes. These measurements were carried-out at 150°F and ambient pressure. Then between 150°F and 200°F pressure was increased to 10,000 psig and stabilized before proceeding with the rest of the test. From the plots, the following can be deduced:

- Below 450°F, there is no significant change in the viscosity profile of Fluid Type-B for a given shear rate. The values measured when heating are quite similar to those obtained when cooling down especially for the 300 RPM test.
- The slight decrease in viscosity in the 450°F tests is attributable to the thixotropic nature of the fluid.
- Due to the considerable change in composition of the original fluid sample beyond 450°F, there is increase in viscosity while cooling down from 600°F as shown in Figs. 11 and 12 for both the 300 RPM and 600 RPM tests.

Conclusions

Based on the results of the experiments contained in this report, the following conclusions are pertinent:

- Fluid Type-A has been shown to disintegrate beyond 425°F and its rheological behavior becomes inconsistent as reflected in the non-uniform increase in viscosity.
- All experimental data on Fluid types A and B suggest a linear relationship between pressure and viscosity while that of temperature is exponential.
- The effects of temperature on viscosity of the oil-based fluids have been observed to be dominant at higher pressures. (>20,000 psig) while pressure effects prevail at lower temperatures (<350°F).
- It has been shown that thermal degradation occurs faster at low pressures (<10,000 psig) than at higher pressures given the same shear history.

- Accurate determination of the thermal breakpoint of a fluid is very important in predicting its rheological behavior. The thermal breakpoints for Fluid Types-A and B were found to be 425°F and 450°F respectively.
- Results from Baseline Tests 2 and 4 indicate that a variation in shear rate over time results in a net reduction in the apparent viscosity of Fluid Type-A.
- The oil-based fluid formulation B1 has been shown to have better thermal stability and lower rheology (up to 600°F) than the formulation B2.
- Fluid Type-B constant shear rate experiments data converge at 550°F. This implies that irrespective of the prevailing pressure, the fluid behavior is similar at 600°F.

Acknowledgments

We are grateful to Baker Hughes Drilling Fluids (BHDF) for providing the XHP/HT viscometer and the drilling fluid samples used during this research. We also acknowledge the technical support by Chandler Engineering.

Nomenclature

<i>API</i>	= American Petroleum Institute
<i>ECD</i>	= Equivalent Circulating Density
<i>ES</i>	= Electric Stability
<i>HP/HT</i>	= High Pressure-High Temperature
<i>OBM</i>	= Oil-Based Mud
<i>P</i>	= Pressure
<i>PV</i>	= Plastic Viscosity
<i>RPM</i>	= Revolutions Per Minute
<i>SG</i>	= Specific Gravity
<i>T</i>	= Temperature
<i>YP</i>	= Yield Point
<i>XHP/HT</i>	= Extreme High-Pressure, High Temperature

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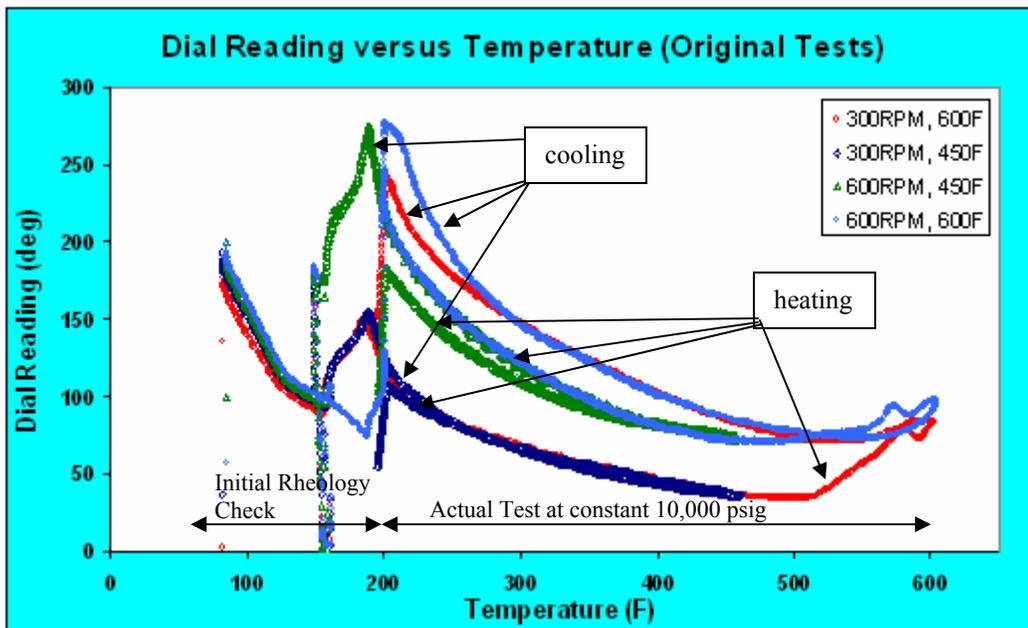


Fig. 11 – Dial reading versus temperature for TX-tests (original)

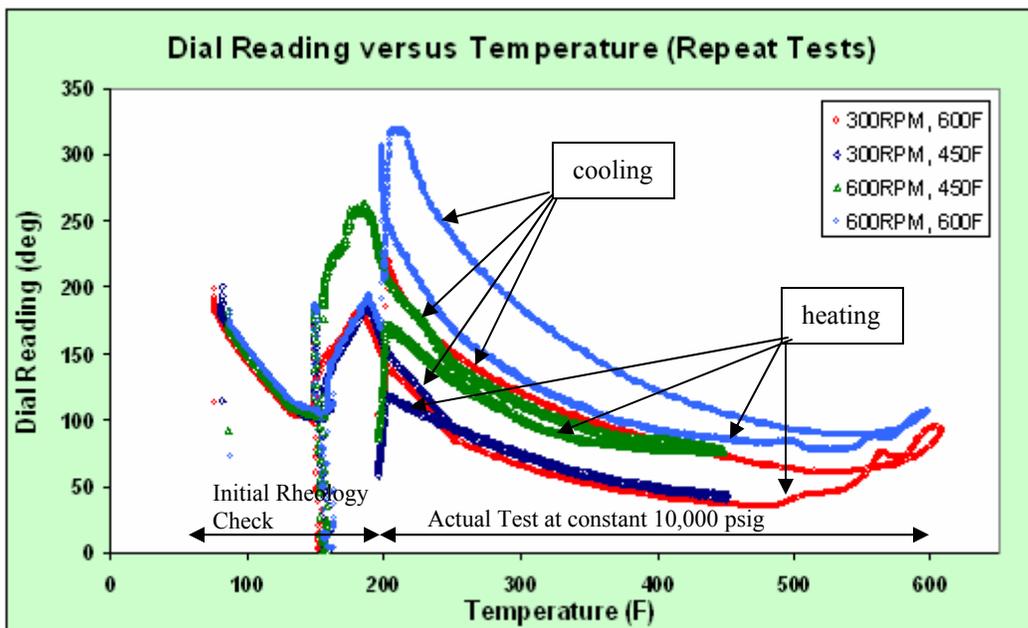


Fig. 12 – Dial reading versus temperature for TX-tests (repeat)