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New Technology to Manage Barite Sag

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Abstract

The occurrence of barite sag has been a well recognized, but poorly understood phenomenon in the drilling industry. Often the conditions under which barite sag is measured in laboratory tests are unrelated to the field conditions under which barite sag occurs. Dynamic barite sag is now recognized as the major contributor to sag-related drilling problems and focus on static sag has rightfully diminished. Dynamic sag is best measured and studied with a flow loop designed to mirror field conditions such as annular flow rates, angle, eccentricity and, to a degree, temperature. Time and manpower resources required to perform flow loop tests are significant and limit the extent to which they are conducted.

Dynamic barite sag is a very complex process that is often difficult to measure, predict and manage. There are two prominent variables conducive to creating dynamic sag; 1) insufficient ultra-low shear rate viscosity (mud-related) and 2) low shear rate conditions (drilling-related). Contrary to common belief, dynamic sag is not entirely a mud-related problem and, under certain conditions, can occur despite appropriate control of drilling fluid viscosity. This paper reviews traditional and newly emerging technology to measure and predict dynamic barite sag. It also reviews the effects of drilling processes on dynamic sag with supporting case history data.

Introduction

Barite sag usually is observed when circulating bottoms-up after the mud column has been static, such as when tripping pipe. Historically it has been associated with a static field environment; consequently test devices and rheological measurements were originally based on static conditions. [1,2,3]

In a departure from conventional methodology, Hanson et al.[4] found that barite sag is most problematic under dynamic, not static, conditions. An important conclusion from this work was that barite sag generally observed in the field is primarily due to barite deposition occurring under dynamic conditions. Building upon this work Bern et al.[5] induced barite sag by circulating at low flow rates with an eccentric drill pipe in flow loop tests. Rotation of the drill pipe tended to prevent bed formation and to aid in the removal of beds. The barite sag tendency of some muds tested was so great that they observed the beds "avalanching" (slumping down the test section and being incorporated back within the system) at low flow rates.

Using a flow loop device and invert-emulsion muds from ongoing field operations Dye[6,7] et al. concluded that severe dynamic sag occurs in eccentric annuli at annular shear rates below 4 s^{-1}. A new field viscometer, capable of measuring shear viscosity at shear rates as low as 0.0017 s^{-1}, was used to measure shear viscosity in this critical shear rate region. Dynamic sag tests and rotational viscometer measurements were made at equivalent shear rates and used to develop a technology that predicts flow loop results from simple viscometer measurements. In addition, certain findings from this study matched earlier work by Bern et al.[8] showing the influence of drilling variables on barite sag. These studies found that the potential for dynamic sag:

- is promoted by an eccentric, stationary pipe such as when sliding in deviated wells,
- increases under low shear rate conditions such as when operating at a nominal annular velocity below 100 feet/minute,
- is not influenced by mud weight, and
- is compounded by increased hole angle.

Barite sag is typically attributed to the mud system and the traditional approach to manage barite sag is to increase rheological properties of the mud system. These efforts are often frustrating because; 1) the proposed solution is ineffective, 2) the solution creates a new problem such as ECD management and 3) expectations are not met. This paper proposes that dynamic sag is related to both the mud system and drilling operation and these two variables cannot be treated independently from one another. Recognition of each variable's influence will help define an appropriate course of action, align expectations and facilitate better management of barite sag.

Mud Variables Effecting Barite Sag

Important advances in understanding the origin and mechanisms of dynamic sag have occurred from flow loop studies, however these devices are not well suited for routine use. Flow loop tests require a significant investment in time and manpower resources, which makes them impractical for most situations. More conventional and simplistic techniques have been developed to fill this void, the designs of which tend towards practical as opposed to technical attributes. The more simplistic tests are designed for rapid analysis and generally are equally suited for field and laboratory use.

This paper will compare technology used to quantify dynamic sag and present data suggesting that one should balance practical considerations with the value and relevance of information derived from simple tests. In addition, a new predictive technology is proposed to bridge the gap and balance the technical attributes of flow loop tests with the practical merits of simplistic tests.

Flow loop tests

Flow loop tests can model field conditions such as annular flow, hole angle and eccentricity, and serve as the benchmark for characterizing dynamic sag under laboratory conditions. The flow loop device shown in Figure 1 has been used to study the relationship between shear rate and dynamic sag using invert-emulsion mud systems in a deviated, eccentric annulus.[6]

An eccentric-wellbore hydraulics model was used to calculate flow rates needed to induce specific shear rates beneath the eccentric pipe. Inputs into the model include pipe geometry, flow rate, eccentricity and coefficients of the Herschel-Bulkley rheological model. In most cases flow rates used provided annular shear rates in the range of 10 to 0.06 s^{-1}. Fluids were circulated for 30 minutes at each flow rate. Typically, four to five tests were performed on a fluid, with each test being made at a progressively lower flow rate. The majority of tests were performed at an angle of 60°, since past studies have shown this difficult for sag management.[6, 8] A few tests were performed at 45° for comparison against data collected at 60°. An operating procedure is listed in the Appendix.

Flow loop testing was conducted concurrently with field operations, presenting a unique opportunity to correlate laboratory and field results. Typically, values of average dynamic sag less than 1.0 lbm/gal in flow loop tests correspond to fluids **not** having barite sag-related problems in the field. Similarly, fluids having barite sag-related problems in the field show a tendency towards average dynamic sag levels above 1.0 lbm/gal in flow loop tests.

Figure 2 shows a comparison of annular shear rates calculated in a 12 ¼" hole section when circulating at 848 US gallons per minute, assuming concentric and 50 % eccentric annuli. Hole angles in this S-shaped trajectory varied from 67.5° in the 12 ¼" open hole opposite 5" drill pipe, to about 44° opposite 8" drill collars. Annular shear rates calculated for the eccentric annulus range from 0.4 to 3.4 s^{-1}, which are significantly lower than the concentric case. Shear rates modeled in flow loop tests realistically mirror those encountered in actual drilling operations.

The following case histories establish correlation between flow loop and field results. Trends in flow loop test data correlate well with field observations of barite sag although the absolute value of barite sag in flow loop tests should not be directly compared to field results.

Case History No. 1 Attempts to run 9 5/8" casing to total depth failed and casing became stuck approximately 500 feet off bottom. Severe dynamic sag was observed when washing down inside of casing with a synthetic-based mud system. Mud weight variations measured at the rig-site when circulating bottoms-up ranged from 12.6 to 17.4 lbm/gal, compared to a nominal mud weight of 14.4 lbm/gal (~ΔMW 2.4 lbm/gal).[6] This mud was then treated with an organophilic clay-based rheological modifier the rig-site, after previously treating and re-testing on the flow loop, and, subsequently only modest variations (ΔMW 0.5 lbm/gal) were measured on bottoms-up. Figure 3 presents flow loop test data on the sample after being treated with a rheological modifier at the rig-site. Flow loop tests compared favorably with field results.

Case History No. 2 The operator repeatedly battled lost circulation in the 12 ¼" section prior to running 9 5/8" casing on this well drilled with a synthetic-based mud system. The mud weight change measured on bottoms-up after circulating on top of lost circulation material (LCM) pills was approximately 0.8 lbm/gal. Dynamic sag measured in the flow loop over a range of flow rates varied from 0.36 to 0.87 lbm/gal (Figure 4). Mud weight variations observed in the field were not associated with the lost return problems experienced in this section.

Case History No. 3 A sample of synthetic-based mud was taken after completion of the 8 ½" section and prior to running a 7" liner. Dynamic sag measured on the flow loop ranged from 0.50 to 0.67 lbm/gal (Figure 5). The maximum differential in mud weight noted while circulating on a wiper trip before running the liner was 0.75 lbm/gal and subsequently the liner was run and cemented without problems. Reports from the field indicated there were no problems associated with barite sag.

Modified rotational viscometer test

The rotational viscometer test (RVT) is a simplistic test used to characterize dynamic barite sag under laboratory and field conditions.[9] The RVT utilizes the measuring geometry of the standard 6-speed viscometer to impart shear at a fixed rate. When rotating at 100 rpm, the shear rate between the outer rotating sleeve and inner bob is ≅ 170 s^{-1}. Dynamic sag is quantified as the change in mud weight after rotating at 100 rpm for 30 minutes. The value of 100 rpm corresponded to maximum sag measured in initial tests and was thought to approximate annular shear rates at which barite sag occurred. Practical considerations governed the choice of 30-minute test duration.

Figure 6 shows that there are actually two sets of concentric cylinders in the RVT: the rotating sleeve/inner bob (A-B) and the outer wall of heat cup/inner rotating sleeve (B-C).[7] Using the dimensions of the heat cup, sleeve and bob the shear rate between the concentric cylinders can be calculated and expressed as a function of the rotational speed of the viscometer. From equation (1) the average shear rate acting across the sleeve and bob geometry is ≅ 1.7 x rpm, while the average shear rate between the heat cup & sleeve is ≅ 0.39 x rpm.

$$\dot{g} = \frac{p \times rpm}{15} x \frac{D_O^2}{D_O^2 - D_I^2} \qquad (1)$$

Fluid volume within the sleeve/bob geometry is ≅ 10 cm³ and ≅ 117 cm³ between the sleeve/heat cup geometry. This equates to a ≈ 10-fold difference in volume outside, compared to inside of the rotating sleeve. Therefore, the RVT has two distinct fluid volumes experiencing different shear rates, making it difficult to determine which are contributing to the measured result.

Modifications were made to the original RVT design to allow for continual density and temperature measurements. Changes included flow ports at the bottom of the heating cup, a peristaltic pump to circulate fluid and a densiometer to measure density and temperature of the circulated fluid. Density and temperature measurements are made at 1-minute intervals for 5 minutes, followed by 5-minute intervals for the remaining test duration (25 minutes).

Comparison of dynamic sag technologies

Dynamic sag was quantified on three invert-emulsion muds using the flow loop and RVT. Figure 7 shows the relationship between shear rate and dynamic barite sag for each of these fluids measured in flow loop tests. Generally, the magnitude of dynamic barite sag increased as shear rate decreased below the 3-rpm equivalent. Flow loop results shown in Figure 7 indicate that Mud #1 has the highest potential for dynamic barite sag.

Figure 8 shows density change versus time for these same fluids measured on the RVT at the standard setting of 100 rpm. RVT data suggest that Mud #3 has the highest potential for dynamic sag. A comparison of the levels of dynamic barite sag measured on the flow loop and the RVT appears in Table 1. Severe dynamic sag observed in flow loop tests with Mud #1 was not apparent using the modified RVT at the standard setting of 100 rpm.

Significant differences are apparent when comparing the geometry and flow paths of the flow loop and RVT. Bern et al.[5,8] and Dye et al.[6] showed that barite sag is most problematic when angle is greater than 30° and generally increases with increasing hole angle. Pipe eccentricity and low annular velocity further exacerbate dynamic sag. The influence of critical parameters such as hole angle, eccentricity and annular velocity on dynamic sag cannot be delineated using the RVT.

Predictive dynamic sag technology

A new and simplistic technology is available that correlates well with flow loop results. This technology was derived from flow loop tests using analytical, not empirical, techniques. Dynamic sag and rotational viscosity were measured at equivalent shear rates and a relationship between the two exists such that one can predict flow loop results using viscometer measurements. This technology possesses the technical relevance of flow loop tests but is simpler and less time-consuming to perform. In most cases this technology is used instead of flow loop tests, which makes it uniquely suited for offshore use.

This technology predicts dynamic barite sag potential through direct measurement of ultra-low shear rate viscosity using a field viscometer (Figures 9 & 10). Viscosity levels below the Lower Limit of the Prevention Window correlate with severe dynamic barite sag observed in the field and laboratory tests, and correspond to a high potential for dynamic barite sag.[6] Conversely, viscosity levels above the Upper Limit indicate a low potential for dynamic barite sag, but are excessive in terms of requirements for barite sag prevention. Finally, viscosity levels within the limits of the Window are preferred, and indicate a low potential for dynamic barite sag (Figure10). In terms of balancing barite sag and ECD management, the viscosity profile of the drilling fluid is optimized within the Window. Data demonstrating correlation between this predictive technology and the flow loop appears in Figures 11-12.

Drilling Variables Effecting Barite Sag

It was recently proposed that barite sag is not entirely a mud-related problem, and that certain conditions in the drilling operation are conducive to creating dynamic sag. Bern et al.[8] presented a very comprehensive analysis of these important variables and provided recommendations in key areas involving well planning and operational practices. Several important findings from this study were later verified by Dye et al.[6] In particular, both studies identified a critical nominal annular velocity value of 100 feet/minute, above which barite bed formation is minimized in flow loop tests. In the case of Bern et al., the value was identified in both concentric and eccentric annuli and in combination with pipe rotation. Dye et al. simulated an eccentric annulus, but without pipe rotation.

Low shear rate conditions

The overall potential for dynamic sag is highest when the drilling fluid experiences low shear rates. Flow loop data and field observations suggest that severe dynamic sag (> 1 lbm/gal) occurs under the combined influence of insufficient viscosity levels (mud variable) and low annular velocity (drilling variable). Sources of low shear rate conditions include, but are not limited to, slow pump rates, tripping pipe and wireline and pipe–conveyed logs. Figure 13 shows a comparison of dynamic sag and average annular velocity for Muds #1 and #2. Dynamic sag increased with both muds at nominal annular velocity less than 100 feet/minute, although there were differences in the severity of dynamic sag within this region. Mud #1 represents a worst-case scenario in terms of mud and drilling variables influencing dynamic sag. The combined effect of insufficient viscosity (mud variable) and low annular velocity (drilling variable) resulted in dynamic sag levels as high as 2.73 lbm/gal (Figure 11 & 13). On the other hand, Mud #2 exhibits sufficient viscosity at ultra-low shear rates, which tends to minimize, but not eliminate, dynamic sag arising from low AV (Figure 12 & 13).

Figure 14 is a plot of flow data comparing dynamic sag and nominal AV on fluids having viscosity levels below the Lower Limit, and thus a high potential for mud-related dynamic sag. The left-hand side of Figure 14, where annular velocity is below 100 feet/minute, corresponds to the highest levels of dynamic sag measured in flow loop tests. Figure 15 shows a similar comparison, however, this plot contains only those fluids exhibiting a viscosity profile within the Window. The main difference between Figures 14 and 15 is the influence of drilling fluid viscosity on severe dynamic sag at low annular velocity, or low shear rates.

Table 2 presents the overall dynamic sag potential based on contributions from the mud and drilling variables. The primary drilling variable presented in Table 2 is nominal annular velocity because it is readily available on the daily mud report. However, other drilling variables, such as hole angle and pipe rotation also effect dynamic sag. Low annular velocity can also arise when tripping pipe or running casing, and may be calculated using equation (2).[10] CF is the "clinging factor" constant, which describes the ratio of pipe diameter to hole diameter. Typical values of CF range from 0.39 to 0.47.

$$AV = \left(CF + \frac{PipeOD^2}{\left(HoleID^2 - PipeOD^2 \right)} \right) * TripSpeed \qquad (2)$$

The influence of hole angle on dynamic sag is enhanced at low annular velocity and with insufficient drilling fluid viscosity. This trend is shown in Figure 14 when comparing the magnitude of dynamic sag at 60° and 45° at nominal annular velocity less than 100 feet/minute. In general, the highest level of dynamic sag in flow loop tests occurred at the highest angle (60°). The influence of angle on dynamic sag decreases with proper control of ultra-low shear rate viscosity (Figure 15).

The following case history provides an example of dynamic sag arising from influences of the drilling operation.

Case History #4

A window was milled inside 11 7/8" casing and a sidetrack section was drilled from 6,951 to 17,190 feet using a 12 ¼" bi-center bit. Maximum angle in the sidetrack section was 65°. The only problems encountered in this section were associated with a "ballooning" formation. Efforts to control the problem required the operator to circulate at AV's as low as 27 feet/minute in the open hole section.

Attempts to run a 9 5/8" liner stopped when the liner became differentially stuck at 11,995' feet, where it was cemented into place, leaving 5,195 feet of 12 ¼" open hole below the liner. A clean-out trip was made after testing BOP's and the well began ballooning, requiring the operator to circulate at AV's from 80 – 96 feet/minute over the course of several days. Pipe was washed to bottom at 19,946 and barite sag was observed when circulating bottoms-up. Mud weights measured at the shaker ranged from 12.5 to 14.7 lbm/gal, compared to a nominal mud weight of 13.7 lbm/gal. This degree of change in mud weight was unexpected since the viscosity profile of the fluid was within the Window (Figure 16), indicating a low potential for dynamic sag. The expectation of those involved in the drilling operation was that little, if any, change in mud weight should occur since the viscosity curve was within the Window.

Upon further review of the drilling variables involved, it was apparent that the hydraulics of the circulating system were compromised due to ECD management concerns and ballooning. The annular velocity in the ≈ 5200 feet of unplanned 12 ¼" open hole was consistently below 100 feet/minute. The data presented in Figure 15 suggests that the origin of dynamic sag was low annular velocity (drilling variable), where moderate levels (~ 0.5 – 0.8 lbm/gal) of dynamic sag arise when operating at low annular velocity.

Another potential source for fluctuations in mud weights, particularly with invert-emulsion muds, is flow line temperature. Unfortunately, the mud weight was not reported in the context of a flow-line temperature on this well. The density of invert-emulsion muds can easily vary ± 0.3 lbm/gal with changes in flow-line temperature; therefore, some portion of the variance is attributed to temperature effects on base fluid density.

Conclusions

- Shear rates experienced in eccentric annuli can be significantly lower than in the concentric case, and below the 3-rpm equivalent of the 6-speed viscometer.
- Trends observed in flow loop tests correlate with field observations of dynamic sag.
- Dynamic sag, defined as a mud weight variation, occurred in all fluids tested in the flow loop. One can determine acceptable levels of dynamic sag in flow loop tests by comparing field and laboratory results.
- The RVT has two distinct sources of fluid volumes; each sheared at different rates that contribute to the mud weight change observed in the test.
- The RVT does not consider effects of pipe eccentricity, annular velocity or hole angle on dynamic sag and did not correlate with flow loop results.
- The Prevention Window accurately predicted dynamic sag potential in all fluids evaluated on the flow loop.
- Dynamic sag arises from influences of the mud system and the drilling operation, and these two are often inter-related.
- The potential for dynamic sag is enhanced when operating at nominal annular velocity less than 100 feet/minute.

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Nomenclature

ECD = Equivalent circulating density
LCM = Lost circulation material
DMW = Change in mud weight, lb_m*/gal*
Rpm = Revolutions per minute
RVT = Rotational Viscometer Test
$\dot{g}$ *= Shear rate,* s^{-1} *or reciprocal seconds*
D_o*= Diameter of outer cylinder*
D_I *= Diameter of inner cylinder*
F = Temperature, °Fahrenheit
PV = Plastic Viscosity, cP
YP = API Yield Point, lb_f*/100 ft²*
10 s Gel = API 10 second gel strength, lb_f*/100 ft²*
10 m Gel = API 10 minute gel strength, lb_f*/100 ft²*
q3 = Fann viscometer readings at 3 rpm lb_f*/100 ft²*
q6 = Fann viscometer readings at 6 rpm lb_f*/100 ft²*
LSRYP = (2 x q3) – q6, lb_f*/100 ft²*
AV = Average annular velocity, feet per minute
OD = Pipe outside diameter
ID = Piper internal diameter
CF = Clinging Factor

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Table 1
Drilling Fluid Parameters

Sample Number	**1**	**2**	**3**
MW, @ 63 °F	13.5	13.9	14.2
600 rpm	126	178	156
300 rpm	73	109	93
6 rpm	7	11	12
3 rpm	6	9	10
PV @ 120 °F	53	69	63
YP @ 120 °F	20	40	30
10 s Gel @ 120 °F	9	13	13
10 m Gel @ 120 °F	18	36	34
LSRYP, $lb_f/100\ ft^2$	5	7	8
Average Δ MW, lbm/gal (Flow Loop)	**1.97**	0.41	0.58
Δ MW, lbm/gal (RVT @ 100 rpm)	0.76	0.49	**0.93**

Table 2
Drilling & Mud Variables Affecting Dynamic Sag

Prevention Window (MudVariable)	**Nominal AV (Drilling Variable)**	**Overall Dynamic Sag Potential**
High Potential	< 100 feet/minute	High (Left-hand side of Figure 14)
High Potential	> 100 feet/minute	Low (Right-hand side of Figure 14)
Low Potential	< 100 feet/minute	Low to moderate (Left-hand side of Figure 15)
Low Potential	> 100 feet/minute	Low (Right-hand side of Figure 15)

Appendix –

Flow loop test procedures
Testing Preparation

1. Add ~ 20 gallons of drilling fluid to reservoir
2. Adjust test section to the desired angle
3. Adjust drill-pipe to the desired effective eccentricity
4. Heat to 120° F and circulate at maximum flow rate

Dynamic Barite Sag Testing

1. Confirm that density is uniform in test section
2. Reduce and maintain a constant pump rate for 30 minutes
3. Measure density at bottom and top sampling ports
4. Average density from bottom and top sections
5. Determine differential between bottom and top sections
6. Flush test section by circulating at maximum flow rate

Static Barite Sag Testing

1. Confirm that density is uniform in test section
2. Reduce flow rate to zero
3. Remain static for 16 hours at 120° F and desired angle
4. Determine density differential as above

Flow loop Specifications
Test Section

1. 2-in ID x 6.7-ft length hollow metal pipe
2. 1-in OD stainless steel, fixed shaft
3. 5 evenly spaced sample ports on lower side
4. 4 evenly spaced sample ports on upper side
5. Wrapped insulation
6. Trace heating elements (± 1° F control)

Test Parameters

1. Flow rate: 0 – 40 gallons per minute
2. Average Annular Velocity: 0 – 288 feet per minute
3. Mud Volume: 15 - 20 gallons
4. Angle: 25° to 70°
5. Eccentricity: 0 – 100 %

Figure 1. Barite Sag Flow Loop

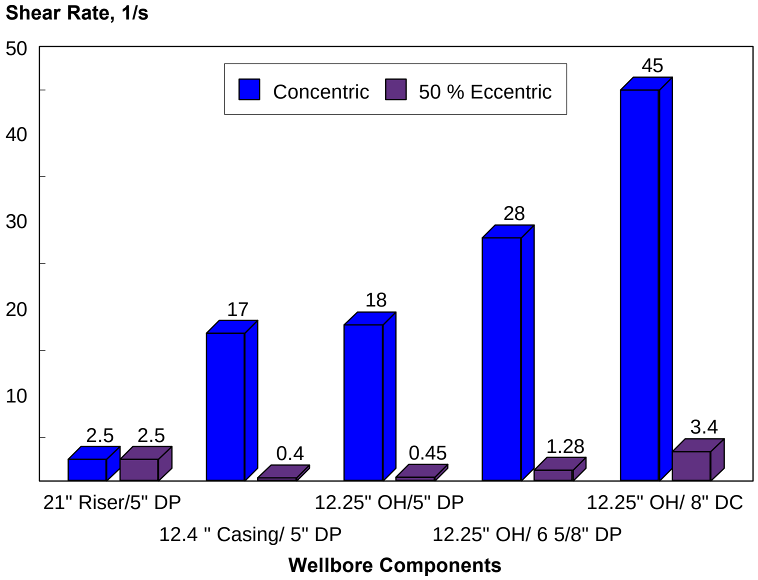

Figure 2. Calculated annular shear rates in 12 ¼" hole

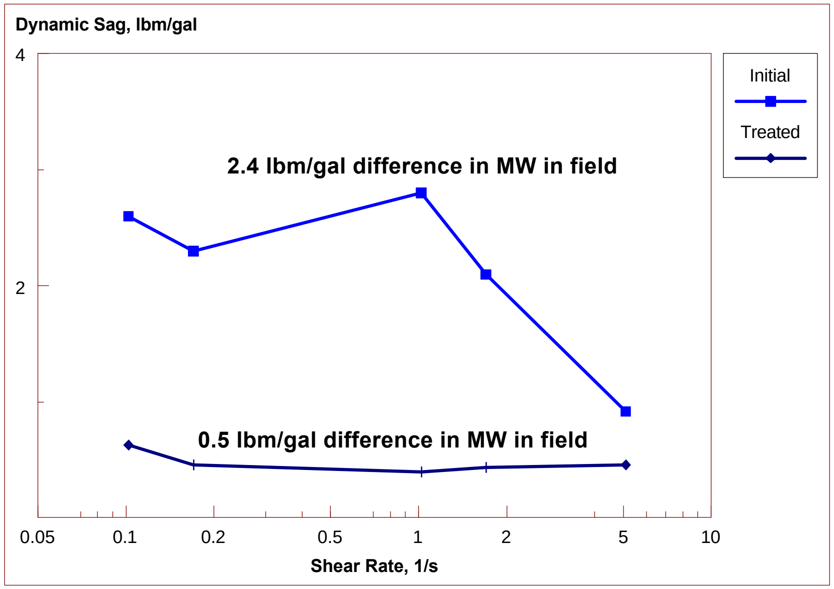

Figure 3. Case History #1 flow loop test results

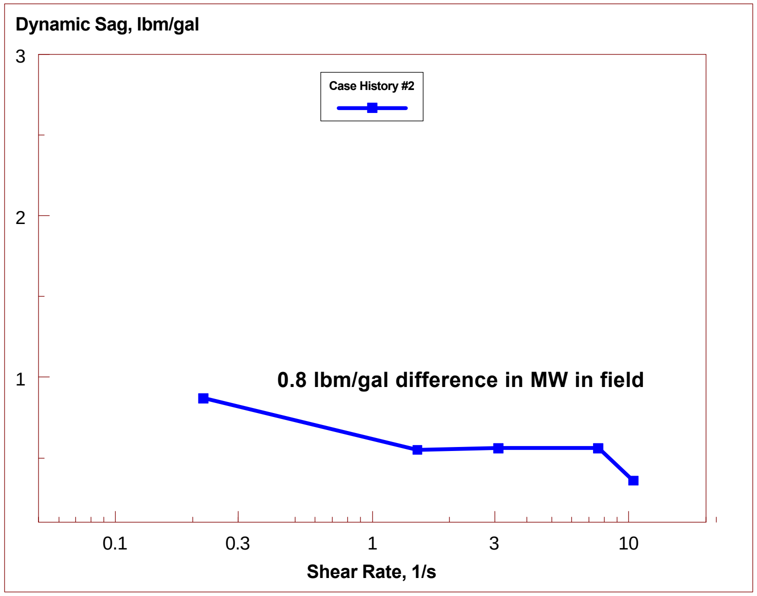

Figure 4. Case History #2 flow loop test results

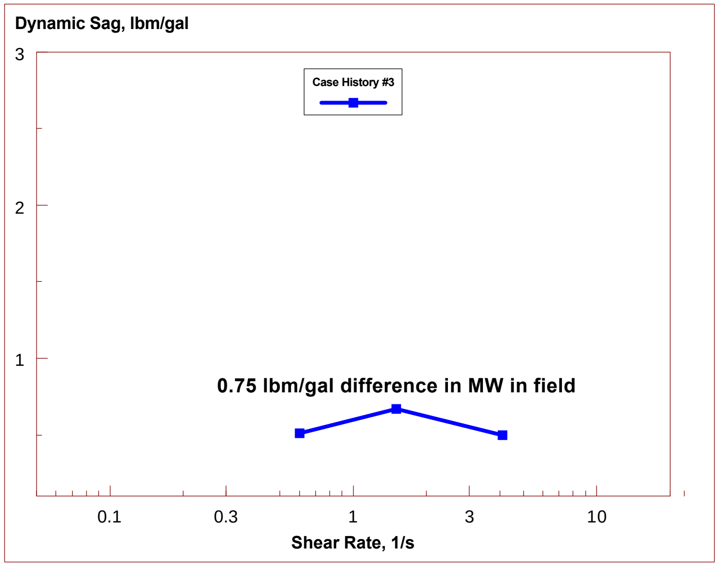

Figure 5. Case History #3 flow loop test results

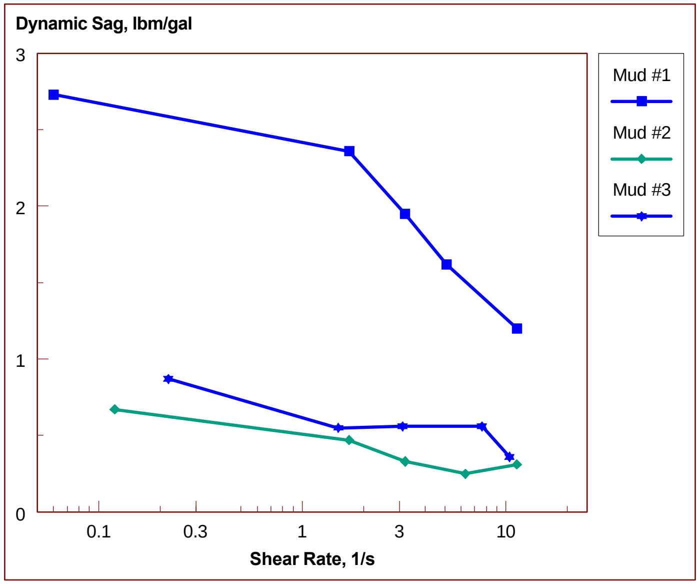

Figure 7. Technology comparison – flow loop results

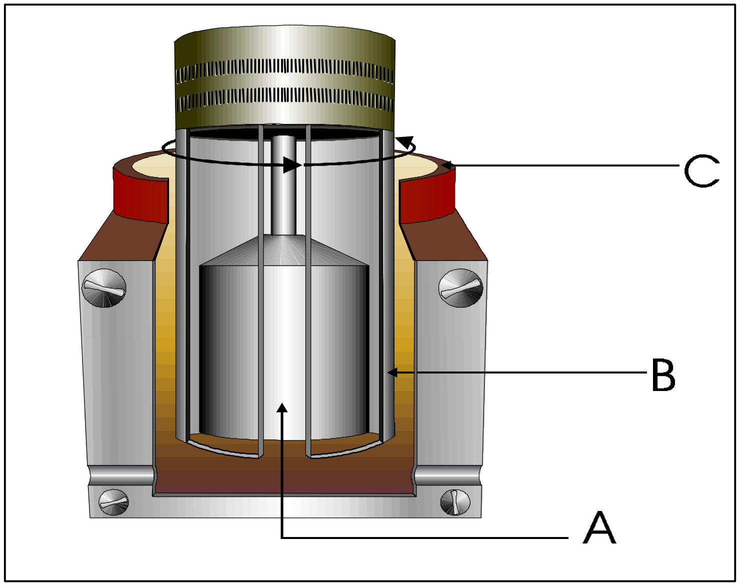

Figure 6. Geometry of RVT dynamic test

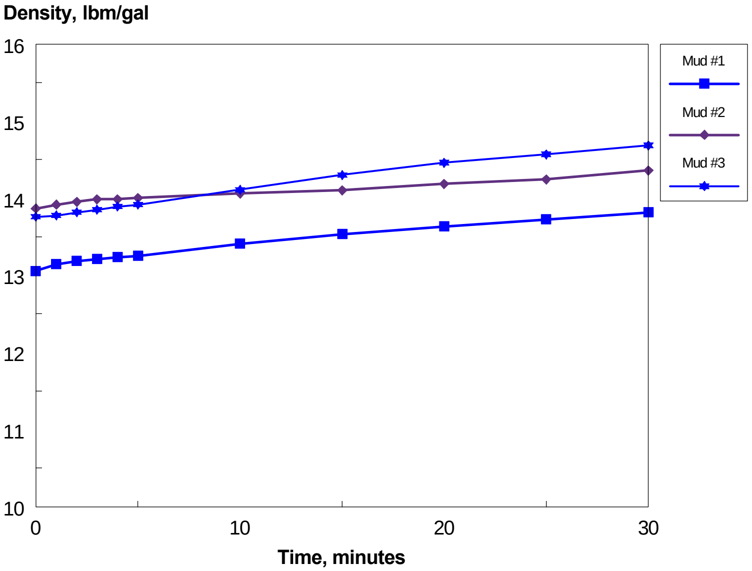

Figure 8. Technology comparison – RVT results

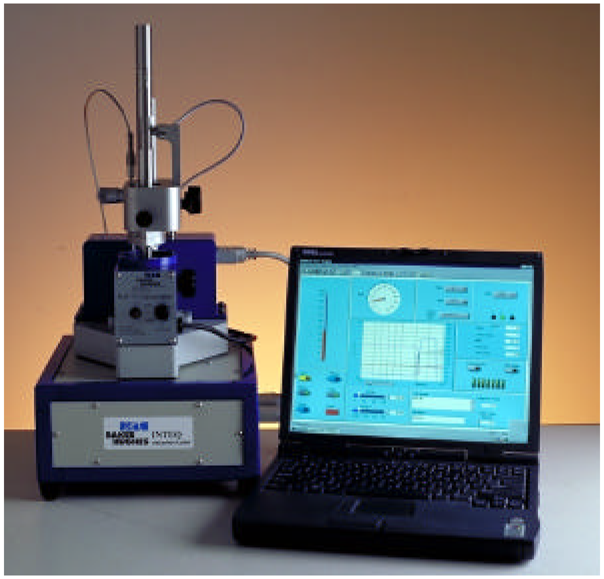

Figure 9. RJF VISCOMETERÒ

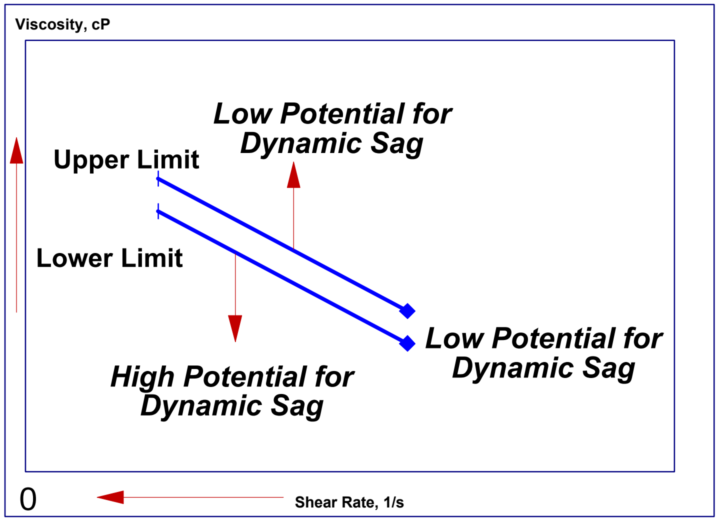

Figure 10. Prevention Window

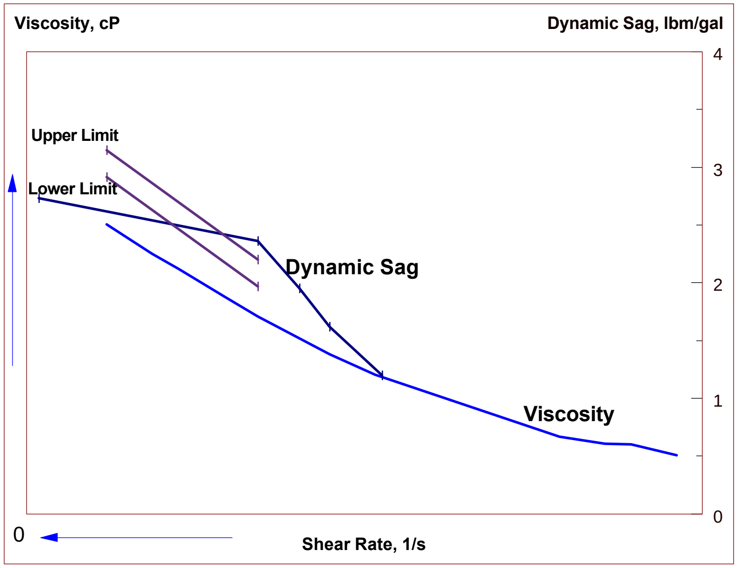

Figure 11. Predictive technology & flow loop results–Mud #1

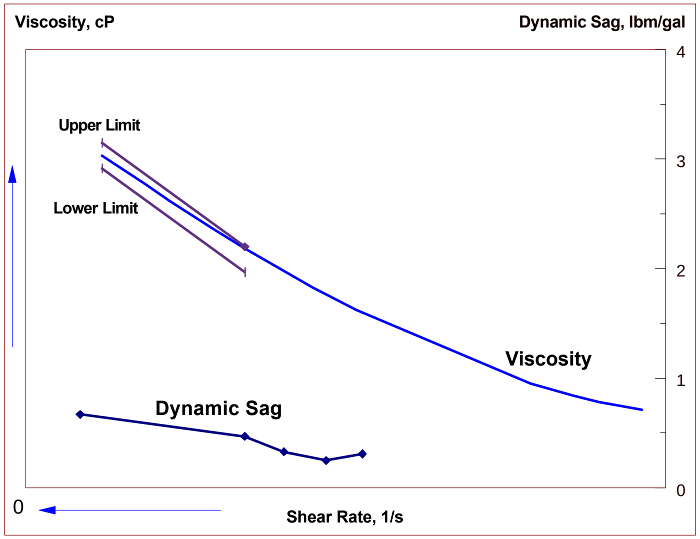

Figure 12. Predictive technology & flow loop results–Mud #2

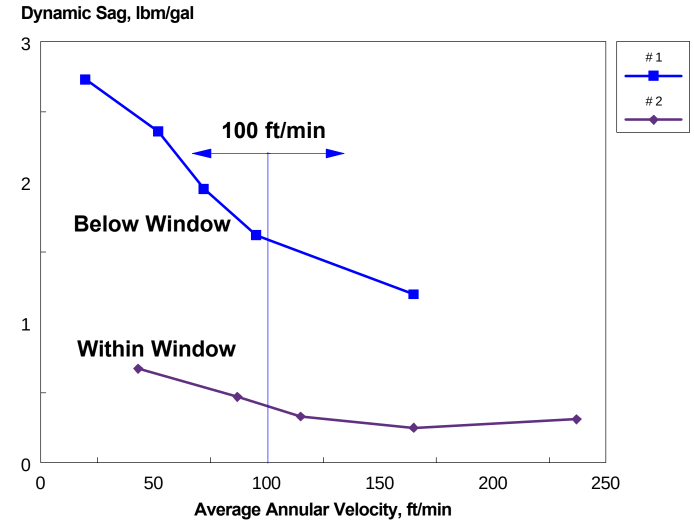

Figure 13. Comparison of AV and dynamic sag in flow loop tests on Muds #1 & #2

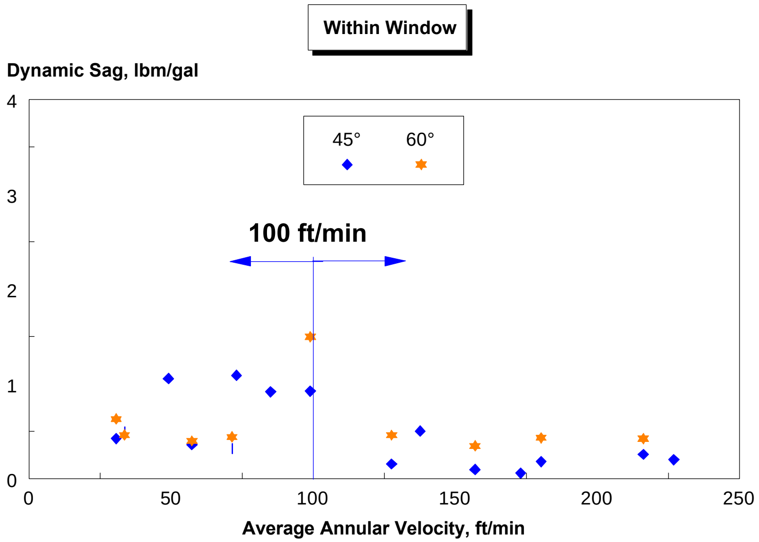

Figure 15. Annular Velocity vs. Dynamic Sag:
Low Potential for Dynamic Sag from Mud Variable

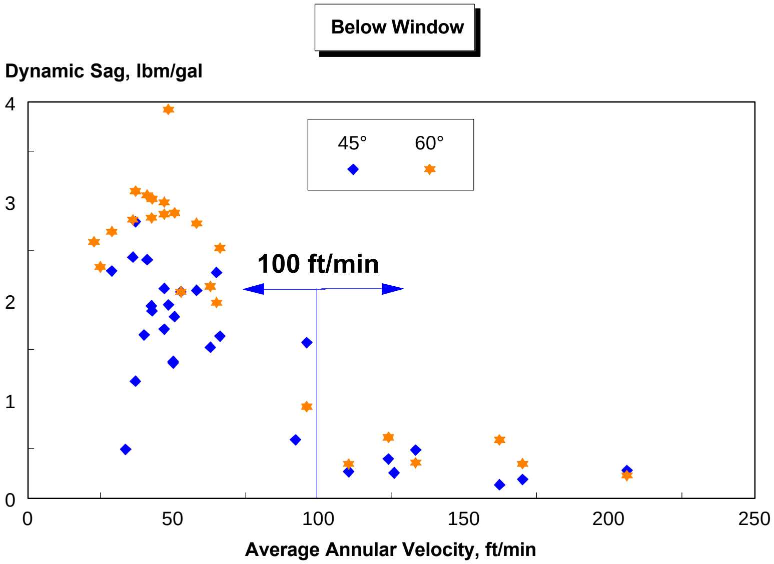

Figure 14. Annular Velocity vs. Dynamic Sag:
High Potential for Dynamic Sag from Mud Variable

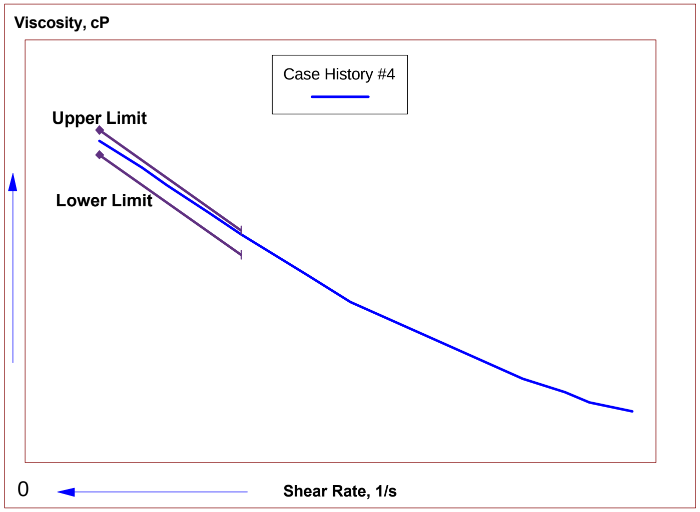

Figure 16. Field viscometer measurements – Case History #4