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Field Monitoring of Weight-Material Sag

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Abstract

Maintaining suspension of weight material in drilling fluids is a crucial part of drilling fluid design. Failure to do so can result in costly problems, negatively impact drilling efficiency, and can ultimately jeopardize overall well objectives. Weight-material sag has been recognized by the industry as a dynamic phenomenon and one that creates a particular risk for highly deviated wells. Whilst the industry's understanding of weight-material sag has evolved, there has not been a widely accepted method of quantifying and monitoring sag at the wellsite.

In 2005, a Work Group was formed by the API to address this gap in the standard suite of drilling fluids measurements. The focus was to develop simple, yet accurate methods, which could be readily implemented at the rigsite. The equipment for sag determination also needed to be suitable for field use and inexpensive. The Work Group proposed a number of simple methods for measuring and monitoring sag. These comprised experimental methods, modeling methods, and a method based on real-time downhole measurement while drilling. The laboratory methods were assessed for accuracy and repeatability via a round-robin testing program. The combined methods provide a valuable means of monitoring weight-material sag at the wellsite.

This paper describes the details of each of the proposed sag-monitoring methods and provides laboratory data from the round-robin testing program. The paper also serves to introduce the industry to a new set of testing techniques that will help identify and manage weight-material sag in field operations.

The final API document incorporating the weight-material sag guidelines is scheduled for publication in 2010.

Introduction

One of the primary functions of a drilling fluid is to maintain weight-material in suspension. Any material that settles no longer contributes to the hydrostatic pressure exerted by the fluid, thus reducing the effective downhole pressure. This can create issues related to pressure imbalances such as influxes and losses. Segregation of weight material can also create mechanical and physical barriers that prevent the efficient running and retrieval of tubulars. The challenges associated with weight-material sag have become more prevalent as the industry has moved to more complex well construction such as high-angle wells, extended-reach wells, and high pressure/high temperature environments.

The industry has recognized weight-material sag as a potential issue for a number of years. There have been many laboratory studies that have determined the primary influencing factors and provide useful guidance in designing drilling fluid properties to mitigate sag.[1] It is also widely acknowledged that sag cannot be totally eliminated and needs to be managed by a combination of good fluid design, good drilling practices, and active surveillance.[2] This paper addresses the latter aspect of surveillance and sets out to catalogue the suite of wellsite tests to assist in monitoring of sag.

The need for the study was identified by the API Steering Committee for Drilling and Completion Fluids. In response, a Work Group was formed with a charge to develop recommended practices for the wellsite monitoring of weight-material sag. The intended audience was the wellsite fluids engineer and the drilling engineer responsible for the overall management of fluids and wellbore hydraulics.

The focus was to develop simple, yet accurate methods, which could be readily implemented at the rigsite. The equipment for sag determination also needed to be suitable for field use and inexpensive.

Project Planning

The selection of the right resources was the key to delivering this cross-industry project in a timely manner. An initial questionnaire was circulated to the operator, service sector, and supplier community to determine the level of interest and commitment to the project. This helped confirm the need for the study as well as identifying willing volunteers who were prepared to devote their time and testing resources to conduct the work.

A detailed project plan was developed for delivering the project in a four-year timescale. The timeline was considered aggressive, but realistic. The main project objective was subdivided into five major technical areas. A primary technical lead appointed for each area held ultimate accountability for delivering the program element. The five primary program areas identified comprised:

- Surface monitoring of weight-material sag
- Sag monitoring based on downhole density

- Dynamic weight-material sag testing
- Rheological measurements of drilling fluids exhibiting sag
- Field sag monitoring based on wall shear stress

In addition to the tasks above, there was also a validation and verification exercise based on round-robin testing. A final program element included the review of novel sag monitoring methods. The intent is that as the novel methods become more mature and widely accepted, they will be considered for future inclusion within the API 13B-2 revision to be issued in 2010.[3]

Each of the areas is described in more detail in the following section.

Summary of Technical Approach

The following summarizes the technical approach adopted for each of the primary sections within the sag monitoring recommended practice. In assessing options that are suitable for field monitoring of weight-material sag the following considerations were taken into account:

- Equipment required must be portable, robust and reliable
- Can be used on a floating installation
- Produces reproducible results
- Simple to use
- Provides results in a timely manner
- Equipment required is inexpensive

The purpose of this paper is to provide the reader with an overview of the methods employed. Precise details required for implementation are included within the full API document.[3]

Definition of Sag

Whilst weight-material sag has been recognized and widely reported within the literature, there is no universally accepted definition of the phenomenon. In order to provide alignment and common understanding within the Work Group, a working definition was developed to describe the process. This common definition was helpful for the project team in defining boundaries and delineating the project scope and plan.

The final definition agreed upon was as follows:

> *Weight-material sag is recognized by a significant (>0.5 lb_m/gal) drilling fluid density variation, lighter followed by heavier than the nominal fluid density, measured when circulating bottoms up, where a weighted fluid has remained uncirculated for a period of time in a directional well. It is recognized that sag is both a static and dynamic phenomenon and has the potential to occur when the drilling fluid is in motion.*

Surface Monitoring

Changes in drilling fluid density measured at surface are often the first indication that weight-material sag is occurring within the wellbore. Variations in drilling fluid density may be identified from the regular surface density determinations that form part of the routine operations, and are recorded in a regular basis during drilling and tripping.

The recommended practice for quantifying weight-material sag from surface density measurement is to capture return fluid samples when tripping-in the hole and stage circulating, or when circulating bottoms-up with the bit at total depth (e.g., prior to tripping out of the hole). An example sag profile is shown in **Figure 1**.

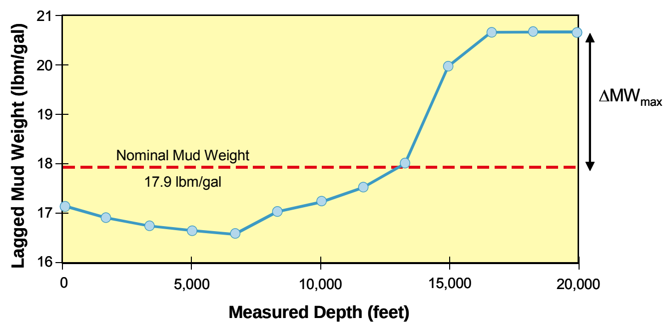

Figure 1: Example surface density profile based on bottoms-up data.

Here the degree of sag is defined as the difference between the maximum mud weight observed at surface and the nominal density of the drilling fluid in circulation:

$$\Delta MW_{max} = MW_{max} - MW_{nom} \quad (1)$$

The surface density determinations should preferably be conducted with a pressurized mud balance to avoid entrapped air. Correction should also be made for the influence of temperature on fluid density. Finally, the lagged depth of samples should take into account known changes in annular capacity due to geometry changes or wellbore enlargement (e.g., wellbore wash-out).

Monitoring Based on Downhole Density

The occurrence of barite sag in a wellbore can be identified by a variety of downhole measurements that include density measurements and pressure measurements converted to equivalent circulating density (ECD). With use of tools that measure downhole pressures, the incidence of barite sag can be seen for both static and dynamic cases. **Figure 2** shows the changes in downhole pressure recorded by a tool while running in the hole where barite sag had occurred.[4] Thought to have an overall density of 13.4 lb_m/gal, the density of the static mud in various sections was seen to be as low as 12.5 lb_m/gal and as high as 19.0 lb_m/gal.

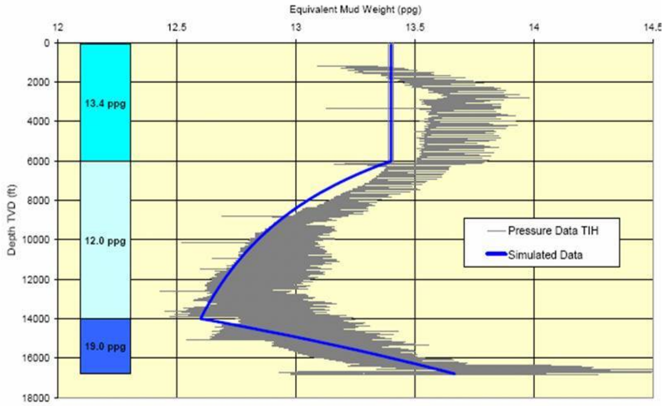

Figure 2: Downhole density changes measured while running the drillstring in the hole.[4]

The interpretation of changes in downhole density when there is fluid circulation is more complex. Under dynamic conditions, changes in downhole pressure can be caused by a number of factors that are not necessarily barite sag related:

- Changes in pump rate
- Changes in rate of penetration (ROP)
- Drillstring rotation effects on ECD
- Downhole fluid density changes resulting from changes in circulating temperature and/or pressure

Correct interpretation of downhole events is thus required. By quantifying the effects of these non-barite sag-related factors, any pressure changes that are barite sag related can be better estimated or determined.

Changes in Pump Rate: When pump rates are increased or decreased, the friction at the wellbore wall is increased or decreased accordingly. Downhole pressure tools measure these changes in annular pressure and are computed to ECD. Changes in downhole pressure caused by changes in the pump rate (ΔP_{hyd}) can be predicted using common drilling fluid hydraulic programs, which can verify whether the measured downhole change in pressure is expected or not. The resulting ΔP_{hyd} can be converted to ΔECD_{hyd} and be removed from consideration in the barite sag investigation.

Changes in Rate of Penetration (ROP): As new hole is being drilled, the incorporation of the drilled cuttings into the fluid flow stream will add to ECD – as long as the cuttings remain suspended and are not lying in a cuttings bed. Hydraulic programs that take account of the ROP effect can calculate the magnitude of any ECD increase caused by the ROP. The resulting ΔECD_{ROP} can then be removed from the barite sag investigation. It should be recognized that in practice, these calculations are further complicated in high angle wells where not all the cuttings are carried in suspension.

Changes in Downhole Fluid Density: Some drilling fluids, particularly invert emulsions and those formulated with oils or other hydrocarbons, exhibit changes in density as a function of temperature and pressure. Often this downhole density (ESD) is different from the fluid density measured at surface (MW). This phenomenon is purely a function of the fluid's compressibility and thermal expansion. These properties can be characterized using coefficients derived from laboratory PVT data. The current API Recommended Practice 13D[5] contains the procedures and coefficients needed to predict the density of drilling fluids as a function of temperature and pressure. Any changes in downhole pressure caused by changes in temperature and pressure of the circulating fluid (ΔECD_{MW}) can then be identified and mathematically removed from the investigation.

Changes in Drillstring Rotational Speed: Variations in the drillstring rotation speed can change downhole pressure measurements. As a general rule, downhole pressures will increase with increasing drillstring rotation speed. These increases in downhole density have been measured in field experiments, and published data[6] show these increases to commonly range between 0.05 and 0.3 lb_m/gal using drillstring rotation speeds of 50-200 rev/min. From a study of a North Sea production well, **Figure 3** shows the changes in measured ECD as a function of drillstring rotation speed for three different flow rates.

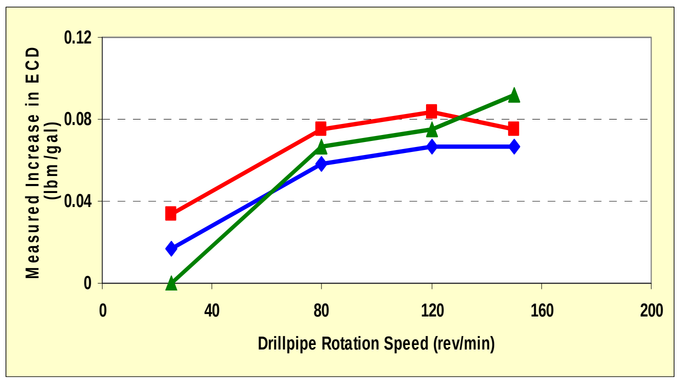

Figure 3: North Sea fingerprinting exercises for three flow rate and drillstring rotation speed combinations.[6]

Data taken from 'fingerprinting' exercises such as these can be used to model the effects of drillstring rotation on annular pressure. Originally, a complex mathematical model for helical flow was constructed to predict the increase in downhole pressure produced by rotation speeds commonly used in the field.[6] Later, a simpler but equally accurate approach[7] was taken that allowed the prediction of drillstring rotation effects to be based on three basic, known parameters:

- Wellbore geometry ratio in the area of interest
- Drillstring rotational speed
- Length of the interval of interest

The easy-to-use equation derived from the modeling calculates the pressure change caused by rotation of the drillstring (ΔP_{rot}). This calculated ΔP_{rot} can then be removed from the measured total pressure change in a barite sag investigation.

Combining the information above can then be used to determine if sag is occurring. The theoretical downhole densities can be calculated for both static and dynamic cases. In static cases, the downhole density should be equivalent to the ESD. Any densities lighter or heavier than the ESD ±0.5 lb_m/gal can be considered as potential barite sag events.

Under dynamic conditions, a downhole pressure change can be described mathematically by the following equation:

$$\Delta ECD_{downhole} = \Delta ECD_{hyd} + \Delta ECD_{ROP} + \Delta ECD_{MW} + \Delta ECD_{rot} + \Delta ECD_{sag} \quad (2)$$

Therefore, if any barite sag is occurring, then the downhole pressure change caused by the barite sag event is then:

$$\Delta ECD_{sag} = \Delta ECD_{downhole} - \Delta ECD_{hyd} - \Delta ECD_{ROP} - \Delta ECD_{MW} - \Delta ECD_{rot} \quad (3)$$

If the resulting ΔECD_{sag} is less than 0.5 lb_m/gal in value, then there is no barite sag predicted mathematically. If this value is above 0.5 lb_m/gal, then there is a potential barite sag event and further investigation is warranted.

Dynamic Weight-Material Sag Test

The Viscometer Sag Shoe Test (VSST)[8] is a wellsite and laboratory test to measure weight-material sag tendencies of field and lab-prepared drilling fluids under dynamic conditions. It is also suitable for screening additives and experimental formulations. Functionally, this method determines the density increase at the bottom of a small container after consistent shearing of the test fluid. The efficiency of re-suspending sagged weight material is an optional measurement that can be correlated to sag-bed removal potential in the field prior to tripping out of the hole.

The VSST designation is derived from the rotational viscometer used as a mixer and the thermoplastic insert (sag shoe) designed to concentrate sagged weight material in the bottom of a viscometer thermocup (**Figure 4**). Not shown in the figure is the digital balance required to determine sample density. The sag-shoe collection well provides a singular location for sampling and reinjecting samples. This not only improves consistency, but also permits measurement of the fluid's ability to pick up a sag bed.

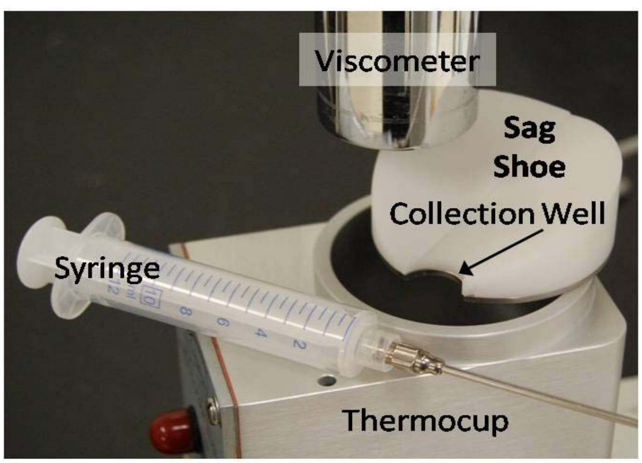

Figure 4: Basic equipment for VSST method (digital balance not shown).

Equipment design is consistent with Darley and Gray[9] who wrote that:

"…*tests at the wellsite must be performed quickly and with simple apparatus...the standard field and laboratory tests which have been accepted by industry are quick and practical, but only approximately reflect downhole behavior. Nevertheless, these tests serve their purpose very well if their limitations are understood and if the data obtained from them are correlated with experience*."

The test procedure involves inserting the sag shoe and then heating a 140-mL sample of weighted drilling fluid in the thermocup to 120°F. Most consistent results are obtained if the starting fluid temperature is close to the test temperature to minimize sag during heating. The 100-rpm setting on the viscometer is then used to generate dynamic conditions. A 10-mL sample extracted by syringe and weighed on the digital balance at the beginning of the test is used to determine the base density (MW_1). After 30 min of shear, a second sample taken from the collection well at the bottom of the heat cup is used to determine the density of the sagged weight material (MW_2). Density increase in lb_m/gal is calculated and reported as B_{VSST} using equation (4):

$$B_{VSST} = MW_2 - MW_1 \quad (4)$$

For the bed pickup test, the 10-mL sample of sagged weight-material in the fluid-filled syringe is first gently re-injected into the collection well. After running the viscometer at 600 rpm for 20 min, a new sample is extracted, weighed, and converted to density (MW_3). The fraction of the sag bed re-suspended by the higher shear rate is calculated and reported as R_{BPU} (%) using Equation (5):

$$R_{BPU} = 100\frac{MW_2 - MW_3}{B_{VSST}} \quad (5)$$

It should be noted that B_{VSST} provides a fluid property without regard to the conditions under which the fluid has been or will be used. As such, a Sag Index has been developed to correlate VSST results with sag experienced in the field. This index is the product of B_{VSST} and four empirical constants based on hole angle, annular velocity, rotary speed and interval length.[10]

Using Rheological Properties to Monitor Sag

There is a generally accepted view that viscosity measurements at low (<1.0 s^{-1}) shear rates and various rheological parameters derived from oscillatory measurements are useful in quantifying the actual or potential ability of a fluid to exhibit weight-material sag. Advanced rheometers are able to measure a wider range of properties than conventional oilfield viscometers and to make these measurements more accurately. Although such equipment is typically unsuitable for use at the rig-site, the additional information that they can generate was considered sufficiently useful for an evaluation of their application to drilling fluid sag measurement to be included in the study.

Drilling fluids which exhibit weight-material sag are, by definition, unstable with respect to time and this makes rheological measurements on them difficult. The magnitude of any measured values can be influenced by sample preparation methods and the shear history of the test fluid. Establishing guidelines for sample preparation and equipment selection will facilitate more meaningful analyses of drilling fluid samples during sag investigations. Historically, there have been no accepted industry methods relating to the equipment or the methodology to be used in the measurement of rheological parameters related to weight-material sag in drilling fluids.

For the purposes of this study, rheometers were distinguished from viscometers by their greater degree of accuracy and range of measurements that they are capable of making. Typical capabilities found only in rheometers are very low shear rates, oscillatory measurements, and the capability to make measurements under elevated temperatures and pressures. They are usually significantly more expensive than simple viscometers and are likely to be incompatible with a drilling rig environment. Rheometers suitable for detailed investigation of sagging drilling fluids should be capable of the following:

- Accurate measurement of viscosity at shear rates from ~1000 s-1 continuously down to 0.01 s-1 or below
- Oscillatory functionality to allow the calculation of the storage modulus (G') and loss modulus (G")
- Accurate measurement of stresses below 0.02 lbf/100 ft^2

Round-Robin Comparison of Rheometers

A round-robin study was conducted involving seven different laboratories each using one of six different rheometers and five different oil-based drilling fluids. One of these drilling fluids was a base formulation with a rheological profile expected to show minimal sag under typical laboratory test conditions. Three of the samples were dilutions of the base drilling fluid with mineral oil at different levels to induce differing degrees of sag potential. The final sample was marked as "unknown" but was in fact identical to one of the diluted samples. This sample was included as a means for providing some assessment of repeatability. This study has been reported elsewhere[11] and highlighted some of the difficulties in achieving consistency of measurement.

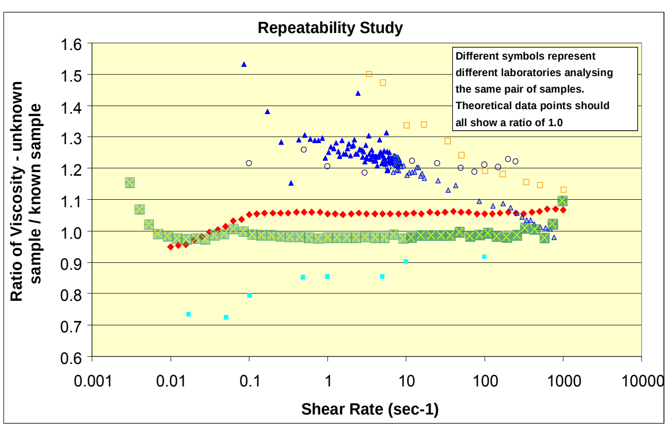

Figure 5: Repeatability of viscosity measurements on drilling fluid samples in a previous sag study.[11]

Figure 5 shows the variation obtained when six of the laboratories in the study each measured the viscosity profile of two samples (one of these was the "unknown" sample) with identical original composition and properties. Some tests gave better results than others and the variations were most probably due to differences in sample preparation.

Detailed below are the key findings of the round-robin study that have an impact on the reliability of measurements to measure and predict sag in drilling fluids:

- Field samples which have been delivered to a laboratory will have been subject to a wide variety of shear histories. In order for laboratory measurements to be meaningful, samples need to be fully reconstituted. If measurements of different fluids are to be compared, it is important to ensure that the fluids are fully reconstituted and resheared to as close to stable properties as possible. Measurements can then be made at differing times after this conditioning.
- Sample mixing should involve the entire contents of the container in which it has been stored. By their nature, fluid samples that have been collected because of sag problems may be expected to have suffered from solids settling during storage. All solids must be removed from the container prior to mixing.
- The sample should be mixed at a high shear rate using a suitable mixer for a period of 15 minutes per 350-mL of drilling fluid. A sample volume of 1,400 mL should therefore be sheared for one hour. Cooling of the sample by use of a water bath should be employed to maintain the sample at 140 to 160°F once this temperature is reached to prevent evaporation of water. If the sample is too large to mix in a single batch, multiple batches can be mixed as above and then subsequently combined. All steps to minimize the time delay between mixing the first and last batches should be taken in such cases.
- For each rheological measurement, the time between the fluid being sheared as described above and the measurement being made should be recorded.
- Immediately prior to each rheological measurement, the fluid should be stirred in the rheometer cup at ~1,000 s-1 for a minimum of two minutes.

Potential Rheological Tests

Through the use of rheometers, a great number and variety of tests may be performed.[11] By exploring several of these tests, a better understanding of the test fluid may be obtained. Tests should be selected and carried out with this goal in mind. Potential tests of interest for examination of drilling fluids include:

- Thixotropy loops (hysteresis) – observing the structure-building tendency of the fluid and how easily that structure is broken by shear
- Yield stress measurements – observing where the

fluid actually yields

- Controlled rate/stress sweep – producing a flow curve demonstrating the relation of stress and viscosity to strain rate
- Oscillatory strain/stress sweep – important for determination of the linear viscoelastic region (for further oscillatory tests) and for determination of the dynamic yield stress
- Oscillatory frequency sweep – giving information on structural behavior of the test fluid over a range of deformation rates, usually performed on a fluid that has been allowed a gel growth period immediately prior to testing
- Oscillatory time sweep – observing how the fluid's structure grows and is maintained under low-frequency deformations over long periods of time, usually performed on a fluid without allowing gel growth before testing

Unlike the common six-speed field viscometer, which exclusively uses a rotating sleeve about a torsion spring bob (Couette geometry), rheometers have a variety of test geometries from which to choose. These include the Couette geometry, double-gap Couette, multi-vane spindles, parallel plates, cone and plate, and any of these modified with roughened surfaces for mitigation of wall slip effects that can occur at very low shear rates. The test geometry should be selected in accordance with the needs of the test to be performed and the fluid being tested.

Sag Test Data Interpretation

Various publications[12,13] have suggested that weight-material sag is closely correlated with the viscosity of the fluid at very low shear rates. The shear rates of interest are typically in the range of 0.1 to 1.0 s^{-1}. Measurement of viscosity at these shear rates was not possible at the rig site using older conventional field viscometers although more sophisticated devices have become available in the last ten years. Advanced rheometers of the type discussed in this paper are also fully capable of making these measurements as part of a basic series of tests designed to provide a complete rheological analysis of a given fluid. Viscosity values, which should be adequate to prevent sag of invert emulsion drilling fluids under dynamic field conditions, have been proposed[13] and a typical graph is shown in Figure 6. In the graph, the solid, parallel lines represent the upper and lower bounds of acceptable viscosity (i.e., viscous enough to prevent dynamic weight-material sag under typical drilling conditions), but not so viscous as to cause other drilling-related problems. Note that the viscosity and shear rate are based on the nominal shear rate calculated for Newtonian fluids. This is consistent with previous publications on this technique. However, the variations arising from the non-Newtonian behavior of typical invert drilling fluids will result in relatively small deviations from these nominal values.[5]

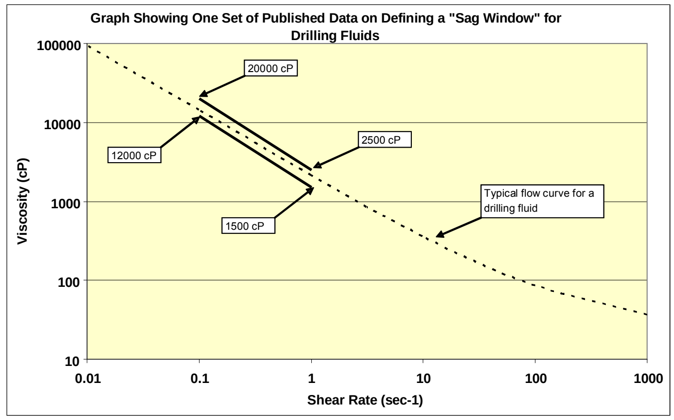

Figure 6 – "Sag Window" for drilling fluids vs shear rate.[13]

Interpretation of data from rheological testing should be made in the context of the specific fluid which is being tested. It is easy to generalize from the rheological behavior of a particular fluid system and attempt application to other systems. However, if the basic characteristics of the systems differ (i.e., different weight materials and oil/water ratios, different viscosifier types, significant changes in internal phase composition, and significantly different emulsifier chemistry), the conclusions of one system may not apply to another. The rheological testing and evaluation of each fluid should be taken with knowledge of the physical characteristics of that fluid. Likewise, all of the rheological testing performed should be considered when drawing conclusions as to a fluid's performance.

It is often beneficial to observe trends in changes of rheological characteristics of a drilling fluid as small changes (treatments) are made to the system. Under such conditions, the effects of such treatments should be monitored. An example here would be evaluating the changes in viscosity with changes in fluid components. One should specifically look for improved/optimal performance in properties (e.g., maximal structure without extreme viscosity or raising ECD issues) based on component changes.

Sag Monitoring Based on Critical Wall Shear Stress

Advanced hydraulic modeling can be used to predict the onset of barite sag under dynamic conditions.[14] In this work it is assumed that barite sag is a dynamic process and that it principally occurs in high-angle wellbores where the rotating drillstring is usually in an eccentric (off-center) position. Accordingly, barite sag will first begin to occur on the low side of the hole next to the wall where there is insufficient fluid stress to keep the moving barite particles suspended. In the earlier works[12], the relationship between fluid stress and maximum measures of barite sag in the laboratory was presented.

Details of the calculation method are described in Hemphill and Rojas[14] and will not be repeated here. However, descriptions of the various calculation steps are made to facilitate understanding of this technique:

1. Obtain drilling fluid rheological properties from viscometer data, from high-pressure/high-temperature viscometers, or from predicted downhole data.
2. Calculate the fluid Herschel-Bulkley rheological parameters as outlined in Reference 5.
3. Calculate the minimum pressure drop required to initiate flow at the wall, using the fluid yield stress (τ_0) and the gap length. Determine the corresponding flow rate for this geometry required to give this minimum pressure drop.
4. For three flow rates slightly higher than that calculated above, determine the corresponding pressure drops and the fluid shear stresses using the generalized Herschel-Bulkley equation for pseudoplastic fluids. Ensure the fluid is in laminar flow in all predictions.
5. Calculate the slope (m) of flow rate vs. fluid shear stress for the three or four cases calculated above. For laminar flow conditions, the slope should be linear or nearly-linear.
6. Calculate the critical wall shear stress (τ_{crit}) for an annular velocity (AV) of 30 ft/min. From earlier published data,[10] maximum barite sag under dynamic conditions occurs around 30 ft/min.
7. Using the calculated value of τ_{crit}, read the predicted maximum barite sag value (ΔECD_{sag}) from **Figure 7**.

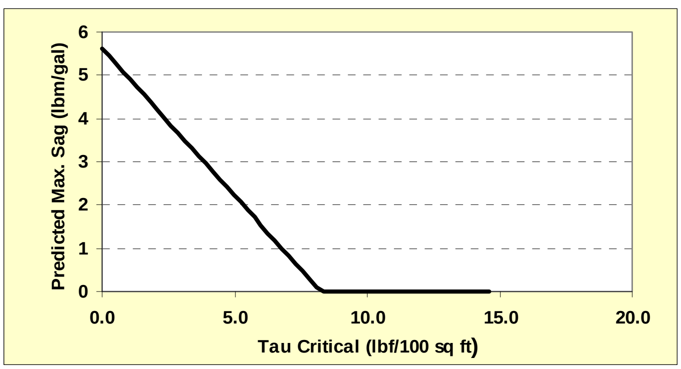

Figure 7: Wall shear stress vs. maximum measured dynamic barite sag.[14]

Round-Robin Testing of Rig-Based Lab Tests

An earlier test program (see above) had evaluated the use of sophisticated rheometers for measuring sag-related properties of drilling fluids. The goal of these round-robin lab tests was to determine if any rig-based tests met the aforementioned criteria (simple, portable, reproducible, rig-capable, quickly done, etc.) and showed significant sensitivity to sag tendency. Tests that meet these criteria would be suitable for inclusion in an API recommended practice.

The Work Group chose to evaluate four existing lab methods: three viscosity-based methods and one density-based method.

- Viscosity over a wide shear range (0.2 to 1000 s^{-1}) by the following three viscometers:
  - OFITE Model 900
  - Brookfield DV-II
  - Grace Instruments M3500
- Density difference using the VSST method

These methods were chosen because they met the criteria of being simple, rig usable, inexpensive, and completed in a short timeframe. To evaluate the methods, it was decided to compare the results of the different methods on four different drilling fluids at seven different industry labs (all part of the Work Group). Each of the labs was able to execute two to three of the four methods to be evaluated. In order to get good results in one round of tests, the Work Group used round-robin lab testing best practices that had been generated by previous API work groups, as well as the results of the preliminary rheometer comparison work. These best practices include very specific procedures, replicate tests, careful sample preparation and distribution, one point of data collection, time limits, and having one technician conduct all the tests at any one lab.

Preparation of Drilling Fluid Samples: A lab-formulated 14.0-lb_m/gal oil-based drilling fluid with very good suspension properties was chosen as the basic fluid, and the other three drilling fluid samples were generated by reducing the clay content of this sample, and increasing the oil/water ratio. Note that the formulation (**Table 1**) includes simulated drilled solids.

To ensure that all the drilling fluid samples were consistent for testing, a preliminary series of tests was conducted with

Table 1: Mud Formulations for Round-Robin Testing of Rig-Based Sag Tests

	Mix Time (min)	Order of Addition	Sample A	Sample B	Sample C	Sample D
Base Oil, bbl		1	0.546	0.549	0.553	0.628
Primary Emulsifier, lb	2	2	7	7	7	7
Lime, lb	2	3	4	4	4	4
Secondary Emulsifier, lb	2	4	5	5	5	5
$CaCl_2$ Brine (22%), bbl	10	5	0.158	0.156	0.157	0.079
Organoclay, lb	10	6	10	7	3	3
Drilled Solids, lb	5	8	25	25	25	15
Barite, lb	5	7	315	317	319	341

these drilling fluids to determine how much shear and hot rolling had to be applied to ensure that the drilling fluids were fully yielded and stable before further mixing by the test labs. It was found that after high shear and hot rolling overnight at 300°F, the drilling fluids maintained their properties when subjected to additional shear and hot rolling. The properties of the large volume of drilling fluid samples mixed for distribution matched those of the smaller, preliminary test samples.

Detailed instructions on how to perform each test method were distributed to the participating labs to minimize variability in the results. Data sheets were distributed to each lab so that the results would be recorded in a common format. Tests were requested to be completed in a two-week timeframe to minimize any variability due to extended aging of the samples on a lab shelf.

Viscosity-Based Methods: To determine repeatability, data was compared for triplicate samples within the same lab, and also for the same sample from lab to lab.

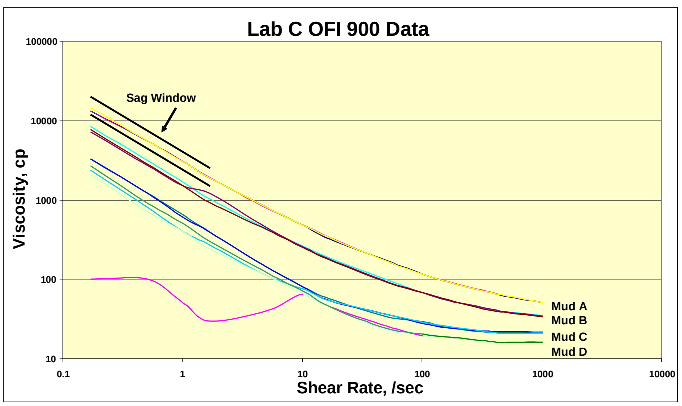

Figure 8: Comparison of rheology data for multiple runs of four drilling fluids within one lab (three runs per drilling fluid).

Figure 8 shows a typical result for one lab of multiple runs with the four drilling fluids on a single rheometer. It is a plot of viscosity versus shear rate, and, in the low-shear region, it includes the "Sag Window" described earlier in this paper. As can be seen, the data clearly differentiate amongst the four drilling fluids. Also, repeatability is good, but suffers with increasing sag tendency of a drilling fluid. The data for Drilling Fluid A fall within the "Sag Window," suggesting that Drilling Fluid A should have low sag tendency.

Figure 9 shows how all three viscometer types evaluated compare on one drilling fluid (Drilling Fluid A) across all labs. Repeatability was good for Drilling Fluid A, but additional data not shown indicated that repeatability suffered somewhat as the sag tendency of the drilling fluid increased. This is consistent with earlier findings that sag measurements exhibit wider variability as the sag tendency of the fluid increases.

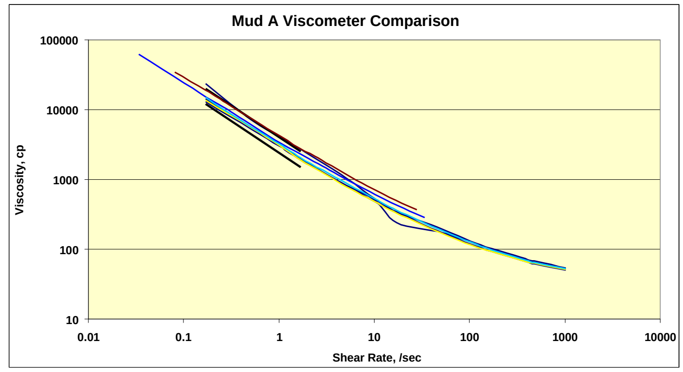

Figure 9: Comparison of Drilling Fluid A data for all three viscometers at all labs

The Work Group concluded from the large amount of data that repeatability was very good for data taken by one lab, and that repeatability was quite acceptable for data taken by different labs. A general trend existed, that repeatability deteriorated for highly sagging drilling fluids. Also, the data showed that all of the viscosity methods discriminated amongst drilling fluids of varying sag tendency.

Density-Based Method: The VSST method produces a value that is the density difference, in lb_m/gal, between the sagged, dense drilling fluid that has settled to the bottom of the cup, and the base drilling fluid. **Table 2** shows the results of the triplicate tests from a typical lab, and the average of all the tests from the seven labs. The table shows that there is some variability among replicate samples. The average standard deviation of the VSST value of the three tests within each lab averaged 0.13 lb_m/gal for Drilling Fluid A (a well-formulated and stable fluid), while the standard deviation of the VSST value among all tests at all labs was 0.25 lb_m/gal. Again, repeatability suffered as the sagging tendency of the drilling fluid increased. For the highly-sagging Drilling Fluid

Table 2: VSST Results from a Typical Lab and the Average of All Lab

	Typical Company				Average of All 7 Labs			
	Sample A	Sample B	Sample C	Sample D	Sample A	Sample B	Sample C	Sample D
Date Tested	5/13/2008	5/13/2008	5/13/2008	5/13/2008	All tests done between 5/2/08 and 5/20/08			
Correction Factor	1.0672	1.0622	1.0522	1.0522	1.0572	1.0418	1.0404	1.0416
VSST, lb_m/gal, Test 1	0.94	1.51	3.63	3.94	1.01	1.77	4.22	4.67
VSST, lb_m/gal, Test 2	0.97	1.69	3.62	4.10	0.93	1.82	4.14	4.70
VSST, lb_m/gal, Test 3	0.88	1.69	3.60	4.35	0.87	1.78	4.08	4.82
Average VSST, lb_m/gal	0.93	1.63	3.62	4.13	0.94	1.79	4.15	4.73
Std. Dev	0.04	0.10	0.01	0.20				
Std Dev all labs					0.25	0.33	0.65	0.67
Std Dev within each lab					0.13	0.13	0.12	0.17

D, the average standard deviation of the VSST value of the three tests within one lab averaged 0.17 lb_m/gal, while the standard deviation of the VSST value among all tests at all labs was 0.67 lb_m/gal.

The table shows that the method discriminated very well amongst the four drilling fluids with differing sag tendencies. It appears that a VSST value of 1.0 lb_m/gal or less would imply a drilling fluid with minimal sagging tendency, while a VSST value over about 1.6 lb_m/gal would indicate the beginning of a possible sag problem. It needs to be emphasized that the magnitudes of the density difference refer to the sag measured in the laboratory and are not directly correlated with the magnitude of sag observed in the field.[10]

B_{vsst} bed pick-up results were less consistent, so this part of the VSST procedure will require further evaluation.

The Work Group concluded from the large amount of data taken that the VSST test repeatability was good and that the ability of the method to discriminate amongst drilling fluids of differing sag tendency also was good.

Novel Sag Monitoring Methods

The Work Group also considered the use of emerging techniques to evaluate sag performance. Whilst these methods are not portable in their current state, it was considered valuable to assess the measuring principles for input into future equipment development. One such method is a solid concentration profiling technique using direct weight measurements.[15] This technique (equipment shown in **Figure 10**) provides an inexpensive field test instrument determining factors critical for sag. The measurement technique is based on Archimedes' principle of bodies immersed in liquid.

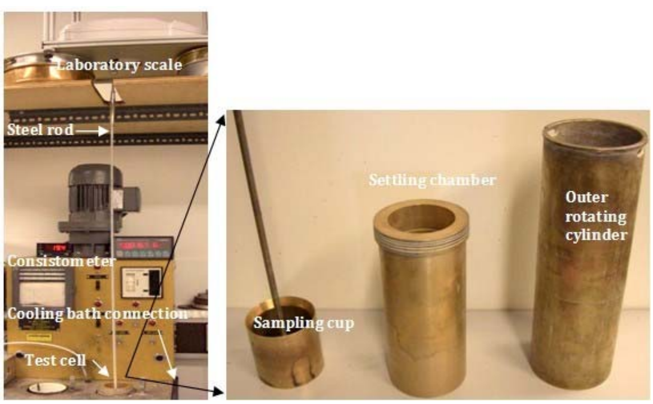

Figure 10: Photograph of direct weight-monitoring equipment

The instrument consists of a laboratory scale coupled with a modified atmospheric consistometer that is described in the well cementing testing standard given by API. The consistometer is standard equipment used for the preparation of well cement slurries prior to rheological measurements or for the determination of thickening time. A benefit of using this equipment design is having the option to use the outer rotating cylinder for running sag tests at dynamic conditions (i.e., with a simulated drillstring rotation). The equipment is furthermore coupled to a cooling bath which makes it possible to run tests both at high and low temperatures. The measurement principle is shown schematically in **Figure 11** where the weight of the settling particles is registered when they settle to the bottom of the sampling cup.

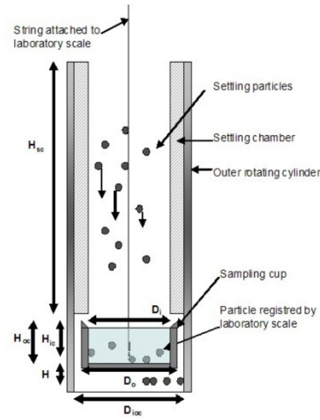

Figure 11: Schematic of direct weight-monitoring equipment.

The instrument gives weight readings when solid particles hit the bottom of the sample cup. From this a settling curve as shown in **Figure 12** can be plotted. From the settling curve one can determine parameters such as total settling potential (w_{TSP}) and instant settling rate (q_s). The fluid composition defines the total settling potential and the total amount of particles that can theoretically settle only accounting for buoyancy effects. Furthermore, one can also describe more universal settling parameters that include area corrections (i.e., a solid flux rate [$g•m^{-2}•s^{-1}$]). This parameter has the potential for being used for other techniques described in this paper as well.

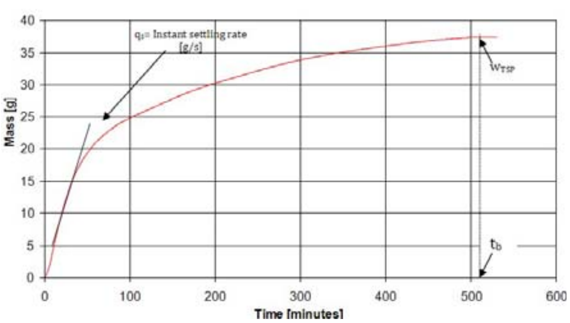

Figure 12: Example output from the direct weight method.

Another approach to the use of density-based measurements to measure dynamic barite sag under controlled conditions involves an apparatus called the DHAST[16] (**Figure 13**). In this specialized unit, a tube filled with drilling fluid set at an angle conducive to barite sag occurrence (usually 45° from vertical). Inside the tube is a rotating shaft that can be rotated at controlled speeds. Clearance between the inside diameter (ID) of the tube and the outside diameter (OD) of the shaft is small (0.2-in).

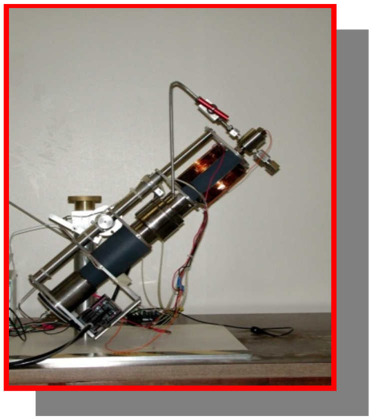

Figure 13: A picture of the DHAST unit in the laboratory.

As barite or other weighting material falls out of suspension when exposed to the low shear rate domain, the solid particles fall to the low side and begin to slide down the tube. As the particles slide, the center of mass of particles begins to change, and the change in the center of mass is monitored as a function of time. A DHAST Sag Rate is then calculated for each test once steady state is reach. Usually at least four tests are run at different shaft rotation speeds (giving different calculated shear rates). Data from the DHAST runs are then used to study the occurrence of dynamic barite sag in a drilling fluid.

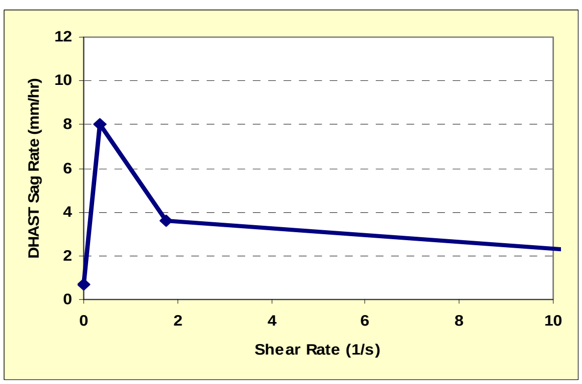

Figure 14: DHAST Sag Rate vs. Shear Rate for a North Sea production well.[16]

Figure 14 shows the results of a study of a North Sea fluid that was known to have sag problems.[1]. The results from use of this unit to study barite sag showed:

- DHAST apparatus sag rates for the static case are usually very low, showing that the drilling fluid has 'fairly normal' suspension properties when the fluid is not moving.
- With increasing shear rates, if the drilling fluid has any potential for barite sag, the DHAST device sag rates will quickly increase. In this case, the maximum sag rate was measured to be 8.0 mm/hr at a shear rate of 0.35 s^{-1}.
- The bulk of the sag occurs in a narrow low shear rate range, consistent with current thinking on barite sag development. Here the bulk of the elevated sag rates occur below 2 s^{-1}. Above the 2 s^{-1} shear rate level, measured sag rates begin to decrease as increased shear begins to promote particle mixing in the fluid.

A fluid having low DHAST Sag Rate values in the low shear rate zone would be deemed one not prone to exhibit dynamic sag in the field. With use of such an apparatus, the sag potential for a given fluid could be determined under dynamic controlled conditions.

Usage Guidelines of Sag Monitoring Methods

This paper summarizes a number of methods that can help drive decisions on issues related to weight-material sag. It needs to be emphasized that no one single method will provide all the answers and indeed the methods available will only give a qualitative trend or guide on whether weight-material sag will create potential wellbore problems.

A number of the methods documented relate solely to the drilling fluid properties in circulation (i.e., the test method has no dependency on wellbore architecture or drilling parameters). Other methods such as direct downhole density determination provide an indication of how the drilling fluid is interacting within the wellbore. In practice it is recommended that a combination of the methods is applied to assist in monitoring the overall drilling operation for early signs of weight-material sag.

If sag is identified as a potential problem, then a number of the listed methods can assist in determining the impacts of chemical treatments on the fluid properties and the resistance to sag. For example, the techniques based on direct density measurement and fluid rheological properties can provide the user with information on the most effective chemical treatments and additional engineering information to ensure that changes to the fluid properties will not be detrimental to the overall drilling operation and will not create excessive ECD resulting in losses.

The final aspect that needs to be emphasized is that optimizing the drilling fluid properties alone cannot be relied upon to provide total assurance against weight-material sag. The drilling operation needs to be viewed as an interactive system and the requirement for careful well design and appropriate drilling practices are essential to minimize the potential for sag.[2]

Summary and Conclusions

A new set of guidelines for wellsite monitoring of weight-material sag have been developed. The guidelines provide the following benefits:

1. A series of wellsite tests has been proposed that can provide an objective assessment of a drilling fluid's tendency to support weighting material.
2. All the methods presented are easy to deploy at the wellsite and do not require specialized equipment.
3. The proposed testing methods are available through API 13B-2: Recommended Practice for Field Testing of Oil Based Drilling Fluids[3].

4. The methods presented need to be used in conjunction with appropriate well designs and drilling practices to manage weight-material sag.
5. The intent is that with time API 13B-2[3] will be updated to include newly developed methods and test procedures for improving wellsite monitoring of weight-material sag.

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Nomenclature

ECD = *Equivalent Circulating Density (lbm/gal)*
ESD = *Equivalent Static Density (lbm/gal)*
Bvsst = *Density increase measured by VSST (lb_m/gal)*
G' = *Storage modulus (N/m^2)*
G'' = *Loss modulus (N/m^2)*
MW_{max} = *Maximum drilling fluid density (lb_m/gal)*
MW_{nom} = *Nominal drilling fluid density (lb_m/gal)*
MW_1 = *VSST fluid base density (lb_m/gal)*
MW_2 = *VSST density of sagged weight material (lb_m/gal)*
MW_3 = *VSST density of pick-up weight material (lb_m/gal)*
R_{BPU} = *VSST calculated bed pickup (%)*
τ_0 = *Fluid yield stress ($lb_f/100ft^2$)*
τ_{crit} = *Critical shear stress ($lb_f/100ft^2$)*
VSST = *Viscometer Sag Shoe Test*
q = *Instantaneous settling rate (g/s)*
w_{TSP} = *Total settling potential (g)*
ΔECD = *Change in ECD (lb_m/gal)*
ΔMW_{max} = *Maximum sag (lb_m/gal)*

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