

# Innovative Lab Equipment Design for Evaluating Weight-Material Sag Under Downhole Temperature and Pressures to Optimize Drilling Fluid Formulations

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## Abstract

A new piece of lab equipment for measuring static settling of weight materials at realistic downhole conditions is presented. This novel method for static aging utilizes a newly designed cell compatible with existing cementing consistometers and curing chambers. Drilling fluid samples are subject to a series of low- and high-pressure aging periods at the same temperature to compare differences in static sag measurements.

Results are presented for comparison testing, which display significant variances in delta density, and syneresis values that can be correlated to a certain degree to material structure.

Industry-standard low-pressure static sag testing has depended on thumb rules and “sag factor” approximations to evaluate sag performance leading, in some cases, to imprecise assessments. Results demonstrate that low-pressure sag results can greatly exaggerate sag compared to testing at actual well pressures and bottomhole temperatures.

Relying on low-pressure sag approximating in many cases can lead to over-treatment with rheology modifiers that can, in turn, prompt higher than enabled equivalent circulating densities (ECD), surge, swab, and pressures to break circulation.

When paired with high-temperature high-pressure (HTHP) rheology measurements, this testing at downhole conditions enables a more accurate assessment of drilling fluid behavior during drilling operations, providing a safer and more cost-effective well execution.

This paper will introduce a new HTHP sag cell, walking through the design and testing methodology. Testing data at wellbore temperature and pressure will be discussed in comparison to existing low pressure methods

## Introduction

Throughout the last decades, the oil industry—particularly the drilling fluids companies—dedicated a vast amount of time and effort to the research of weight material settling. This has been an important focus since the inability of the drilling fluid to suspend the weight material could have catastrophic consequences, such as the loss of the well integrity. As a result, numerous papers have been published on the subject proposing innovative laboratory testing equipment, field methodologies,

and recommended field practices to reduce the likelihood of experiencing weight material sag incidents.

Two of the weight-material sag evaluation methods proposed in the literature that have been used extensively in a lab environment and the field are the dynamic weight-material sag test and the sag window. Both methods are included in the 2014 update of the API SPEC RP 13B-2 (API 2014).

However, developing a single method, preferably a field-friendly procedure, that would deliver an accurate and absolute assessment of the dynamic and static weight-material sag potential continues to be a quest. It is an even greater challenge now that the design of the latest generation of synthetic based fluids includes changes in material structure. These changes aim to provide low ECD, which could be seen as an opposing target to weight-material suspension capabilities.

This paper presents a newly designed HTHP sag cell (HTHP-SC) to conduct weight-material sag evaluation under static conditions at realistic temperature and pressure and discusses the results of long-term static tests compared to standard low-pressure aging trends.

## Weight-Material Sag Framework

API SPEC RP 13B-2 recognizes weight-material sag as a dynamic and static phenomenon. However, currently, the lab methods described in the recommended practice are intended to provide insight into the sag tendencies of drilling fluids when in a dynamic state.

With the aim of setting the stage before discussing the lab equipment developed to estimate static sag tendencies, this section presents a high-level discussion of the most common and current laboratory methods used to assess both dynamic and static weight-material sag.

## Dynamic weight-material sag

Weight material sag has been studied intensely in the last three decades but with a heavy focus on settling material under dynamic conditions. The reason is partly due to laboratory experiments conducted in the early '90s using sag flow loops (SFL), which produced results showing that dynamic conditions would generate more pronounced weight-material sag events than those observed under static periods. Recommendations on operational procedures and fluid

treatment were generated based on SFL results. (Hanson, et al. 1990).

In the past decade, efforts have been made toward developing advanced SFL equipment that would enable onsite monitoring of sag tendencies (Troncoso, Slater and Jaimes 2018). However, SFLs have been mainly restricted to the planning stage of a project or as part of post-analysis investigations.

A simple and field-friendly laboratory method developed to assess dynamic sag potential is the viscometer sag shoe test (VSST). This test is currently one of the API-recognized dynamic sag tests along with the sag window. The VSST is attractive for field use because it is a relatively easy test to perform and does not require additional or expensive lab equipment. But the results should be taken as relative and should not be correlated directly with field sag results. (Zamora 2011).

### **Static weight-material sag**

In assessing weight-material static sag potential, the typical test methodology used is relatively straightforward and encompasses typically aging a 350-ml mud sample in a 500-ml stainless steel cell for a specific period at the target bottomhole temperature (BHT).

Depending on the test temperature, a backpressure is applied using gas (nitrogen) to avoid the evaporation of the fluid or the internal phase in the case of testing a NAF. Once the aging period is completed, the cell is cooled down in front of a fan to room temperature, the free fluid on top of the mud sample is removed and the remaining mud in the cell is split into a determined number of layers. The density of each of the layers is measured and recorded.

As with some other laboratory tests used in the drilling fluids industry, the lab methods that offer advantages, such as those tests that are conducted without requiring specialized equipment, usually are performed at conditions that do not fairly reflect actual field environments and are normally run for screening purposes or evaluation of trends. That brings about a high level of uncertainty when the interpretation of the results is not done correctly or correlated with other fluid properties and trends, or when the results are extrapolated outside the scope of the lab test.

Specifically for the static sag test conducted at low pressure, the head space in the cell enables the continuous phase of the drilling fluid to migrate and locate on top of the fluid column as depicted in **Fig. 1**. Such behavior is obviously not truly representative of the fluid behavior in a field environment.

Relatively easy modifications to the low-pressure sag protocol have been done, for example, factoring in the well angle via incorporating a holder set at the angle of interest, generally at 45°. However, one of the downsides of aging the fluid at an inclined position is the process of sampling the layers after the test period. Sampling at an angle incurs the risk that layers may come together.

Moreover, as mentioned previously, even when an angle is added to the test, failing to use a representative pressure during the aging period has demonstrated that the test results could

exaggerate the sag tendency of a fluid.

Despite the known limitations, rules of thumb or so-called sag factors are commonly calculated when designing a fluid, or during the execution of a project to estimate the sag tendencies and guide fluid treatments. A sag factor of 0.5 represents zero static settling. Values greater than 0.53 are an indication of a fluid with high risk to settle. (Gao 2000).

As noted earlier, even though API SPEC RP 13B-2 recognizes that weight-material sag can occur in dynamic and static conditions, the laboratory methods currently available in the recommended practice are the VSST and sag window. Both methods, however, are intended to provide guidance in relation to sag tendencies in dynamic conditions. Without having an API-recognized lab method, the static sag test protocol can differ, as does the equation to calculate the sag factor.

Sag factor equations are straightforward, but the results could differ significantly if the equation is a function of the original fluid density or the density of the top layer after removing the free oil.

As with other lab test results, low-pressure sag factors are indicative and should be used in conjunction with other fluid properties. For example, if the sag factor is calculated using the density of the bottom and top layers in the cell—excluding the free oil—the volume of the free oil should be reported, as well as a measurement of the shear strength of the fluid in the aging cell.

When conducting low-pressure sag tests, another variable that has shown to have a substantial impact on the settling of weight material is the time since homogenization of the fluid before setting the cell to static aging. (Bouguetta, et al. 2020).

### **Weight-material sag evaluation approach**

As concluded in a recent study of dynamic and sag lab results on lab-built fluids and field mud samples, there is no a standalone evaluation method that can absolutely define the settling mechanisms in nonaqueous drilling fluids (Zeng 2016). Thus, combining both static and dynamic assessments of drilling fluids under specific stress conditions would provide greater understanding of the propensity of such fluid to sag.

The importance of evaluating the dynamic sag potential of a fluid is well recognized. The static analysis should be included in the scope of works when designing a fluid, especially when the drilling operation involves operations with prolonged static periods under harsh downhole conditions in complex well geometries.

Due to the great exaggeration in static sag tendencies when conducting the sag tests at low pressure, a new HTHP-SC is presented to measure weight-material settling at realistic field conditions.

With this new HTHP-SC design, long-term static aging can be performed in a safe manner, without adding much complexity to the test method, eliminating any possible cross-contamination with the base oil used to pressurize the fluid.

The HTHP-SC has already been used in the design stages of highly complex well that have required prolonged static times for special testing operations.

## HTHP-SC Design

The HTHP-SC was designed for use in existing cementing equipment, rather than an entirely new testing apparatus. Two commonly used cementing testing machines with the ability to heat and pressurize the HTHP-SC are curing chambers and consistometers. Both devices use mineral oil as the pressurizing medium in conjunction with programmable temperature and pressure controllers. They are typically connected to data acquisition software for remote monitoring throughout the testing duration. Taking advantage of the remote monitoring can provide much needed testing flexibility and maximize equipment utilization when drilling fluids and cementing labs are co-located.

Pressurized consistometers (**Fig. 2**), with minor modifications, can be repurposed to accommodate the HTHP-SC and run as a curing chamber for the duration of the test. The pressurized consistometer is a common piece of equipment found in cementing labs typically used for relatively short dynamic testing. A pressurized consistometer measures the thickening time of a cement slurry under temperature and pressure (API 2013).

The HTHP-SC is also compatible with larger curing chambers (**Fig. 3**). For these, no modifications are needed to load and run the HTHP-SC. The pressurized curing chamber is used primarily to cure 2-in cement cubes and cement cores for mechanical properties testing and API SPEC RP 10B-2 sedimentation testing. This equipment is more suitable to long term testing scenarios.

In addition to the cost considerations of manufacturing a cell compatible with already existing HTHP equipment, using a cell within a pressure chamber is inherently safer than a stand-alone cell design. Since the cell operates with a floating piston and is submerged in a pressurized fluid, there is no differential pressure between the inside and outside of the cell itself. Furthermore, there is a safety rupture disc built into the piston that will burst in the event of excessive differential pressure.

The cell is designed for testing with 450 mL drilling fluid, versus the 350 mL used in a conventional low pressure aging cell. Working with greater volumes reduces the margin of error due to measuring fluid volumes and densities. For more accurate temperature control, there is a temperature probe tube running through the center of the cell. Taking advantage of this probe is more accurate than relying on the on-board temperature thermocouples at the chamber wall of the consistometer or the bottom probe on curing chambers.

The HTHP-SC features a floating piston that sits above the drilling fluid and enables pressurization of the sample while eliminating the air/nitrogen gap that exists in a low-pressure test. The piston has a bypass port that enables the top two thirds to be extruded through the floating piston. For applications where the drilling fluid contains lost circulation material (LCM), there is the option to simply remove the piston and manually remove the top two fluid layers. To extract the bottom third layer, the cell is equipped with an integrated bottom cup

that detaches from the cell body.

## Testing Methodology

To load the HTHP-SC, the drilling fluid sample to be tested is homogenized and poured into the cell. A small amount of excess mud is added to the cell to ensure there is no air gap between the piston and drilling fluid sample. The piston is installed into the cell with the bypass port open, and a spacer tube that is specifically machined for loading the cell is used to push the piston down in place so that there is exactly a 450 mL sample in the cell.

The cell is then lowered in the consistometer or curing chamber. Then the chamber is filled with pressurization oil and the chamber lid is sealed. A temperature and pressure ramp-up is performed based on temperature targets. Once the testing conditions are achieved, the testing time begins and is monitored throughout the aging period. At the end of the aging period, the heating is turned off, enabling the chamber and sample to cool to a safe handling temperature. Depending on the model of equipment used, there may be water cooling lines that can be utilized to speed up the process.

Once the chamber and cell have cooled, the pressure of the chamber is bled off and the HTHP-SC is carefully removed. Sized spacer tubes are used for extracting the free oil, top third layer, and middle third layer. The bottom third layer is contained in a cup that is unscrewed from the body. The free oil volume and densities of each drilling fluid layer are then measured.

## High Pressure Sag Results

Static sag data has been generated using the newly designed pressure cell to aid in the formulation of NAF for challenging offshore environments. For one of the deepwater applications where the pressure cell was used, the fluid design entailed a delicate balancing act between weight-material sag performance and a rheological profile that would deliver low ECD values since the application was for a narrow drilling window interval. As previously mentioned, those two requirements: long-term dynamic and static weight-material suspension, which would appear at first as mutually exclusive, are now the norm for complex drilling environments such as extended and ultra-ERD, high-temperature high-pressure reservoirs, and deepwater, and ultra-deepwater wells.

The NAF fluid for the application mentioned above was formulated with a base oil with relatively high kinematic viscosity at low temperatures that made the design of the low ECD, as evaluated via hydraulics simulations using high-temperature high-pressure (HTHP) rheology, more demanding. Chemistries that had not been used in the project area were introduced as part of the fluid formulation to achieve the right HTHP rheological profile. The chemistries were also used to create the desired weight material suspension for the drilling of the interval and the static periods when performing the logging program. The fluid was tested at the maximum project BHT and bottomhole pressure (BHP) for up to 30 days to assess the emulsion stability and sag performance of the fluid during the

drill stem test (DST). **Table 1** presents general information on the fluid formulation.

The static sag results obtained with the HTHP-SC were compared to those obtained at low-pressure. **Table 2** shows a summary of the test conditions and the corresponding free oil % and the mud weight (MW) of the bottom layers. The reduction in the delta MW when using high pressure was, on average, 80% for the 7-d and 15-d aged samples.

High-pressure sag testing was conducted for up to 30 days, which was the projected period to perform the DST. The objective of the extended aging test was to first confirm the stability of the emulsion and second, ensure the suspension capabilities of the fluid at the highest temperature and pressure projected for the reservoir section. The sag results obtained in the long-term aging test showed a correlation between sag performance and material structure. That behavior agrees with studies on particle sedimentation performed on fluids exhibiting the same yield stress rheological profile but with different colloidal microstructures. (Emady, Caggioni and Spicer 2013).

Even when there have been efforts to develop correlations between rheology and dynamic and static sag behavior, care should be taken when using such protocols or rule of thumbs. These rules are unlikely to be universal even when studying fluids that use new chemistries, for example, NAF intended to provide low ECD values.

## Conclusions

Utilizing the HTHP-SC for the aging of drilling fluid at downhole temperature and pressure shows a significant reduction in static sag measurements compared to testing in low pressure aging cells. Furthermore, there is a reduction in the syneresis of base oil that may be attributed to the higher pressure or fluid expansion and the removal of an air gap in the head space of the test sample. Moving toward a more representative form of testing will enable drilling fluid experts and drilling engineers to optimize fluid specifications at downhole conditions.

In addition, the newly designed HTHP-SC produces results in line with other existing HTHP aging units, while also making several improvements. Having a cell that can be used with existing equipment enables significant cost savings over stand-alone units, while improving equipment utilization. Other methods involve custom installed units with large pumps and exposed high-pressure tubing versus the self-contained cementing units. Having the HTHP-SC aging within another pressure cell not only improves the safety aspect, but also enables for faster heat up and cool down due to thinner cell wall requirements.

Ongoing testing is currently being conducted to further determine the effect on NAF fluid static sag tendencies with various selections in rheology additives and changes in material structure.

As the demand for more sustainable high-performance water-based muds continues to increase, there are also plans to utilize the HTHP-SC to better optimize these fluids at downhole conditions.

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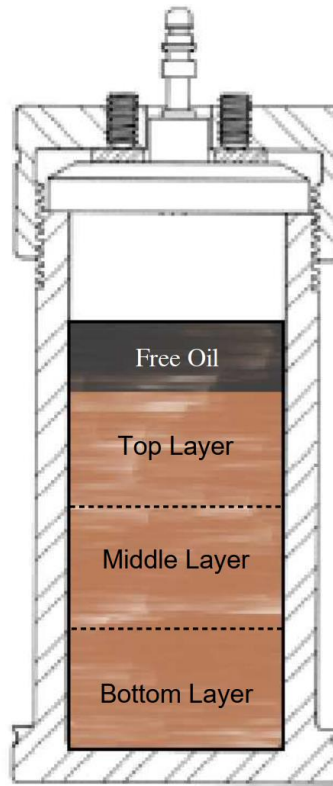


Fig. 1–Diagram of low-pressure aging cell and fluid column when conducting a low-pressure sag test.

Additive	lb/bbl
Paraffin oil	Required
Organophilic clay – 1	1.75
Organophilic clay – 2	0.75
Alkalinity	3.00
Emulsifier – 1	10.00
Emulsifier – 2	2.00
Wetting agent	3.50
Conditioner	4.00
Fluid loss control additive – 1	1.50
Fluid loss control additive – 2	2.00
CaCl <sub>2</sub> brine	Required
Barite	Required
Rheology modifier – 1	8.00
Rheology modifier – 2	0.25
Bridging material	20.00

Table 1–Formulation used for sag evaluation with generic product names

Aging temperature	°F	311	311	280	280
Aging time	days	7	7	15	15
Aging pressure	psi	Low P	High P	Low	High P
Free fluid on top	v%	7.7	1.2	15.8	3.1
Initial fluid density	lb/gal US	16.86	16.86	16.86	16.86
Bottom layer density	lb/gal US	18.98	17.32	20.78	17.57
$\Delta$ MW	lb/gal US	2.13	0.46	3.92	0.72

**Table 2—Results of low-pressure and high-pressure sag tests for 7-d and 15-d aging periods.**



**Fig. 2—Pressurized consistometer, with chamber close-up on the right. The HTHP-SC is designed to fit into this chamber.**



**Fig. 3—Pressurized curing chamber, with larger chamber close-up on the right. This equipment is more suitable for long-term testing.**

## Nomenclature

*BHT* = Bottomhole temperature  
*ECD* = Equivalent circulating density  
*HTHP* = High temperature high pressure  
*HTHP-SC* = High temperature high pressure sag cell  
*NAF* = Nonaqueous fluids  
*SFL* = Sag flow loop  
*VSST* = Viscometer sag shoe test

## References

- API SPEC Recommended Practice 13B-2, Fifth Edition, April 2014
- API SPEC Recommended Practice 10B-2, Second Edition, April 2013.
- Bouguetta, M., Jimbi, E., and Jaimes, J.P., et al., 2020. “Top 5 Recent Learnings in Drilling Fluids Laboratory Testing—Building Upon the Guidelines of API RP 13 and Other Industry Recognized Procedures,” Paper presented at the AADE Fluids Technical Conference and Exhibition.  
<https://www.aade.org/application/files/9915/9179/4736/AADE-20-FTCE-104 - Bouguetta.pdf>
- Emady, H., Caggioni, M., and Spicer, P., 2013. “Colloidal Microstructure Effects on Particle Sedimentation in Yield Stress Fluids” *Journal of Rheology* Vol 57, pp 1761  
<https://doi.org/10.1122/1.4824471>
- Gao, E., Booth, M., and Niall MacB., 2000. “Continued Improvements on High-Pressure/High-Temperature Drilling Performance on Wells With Extremely Narrow Drilling Windows—Experiences from Mud Formulation to Operational Practices, Shearwater Project,” Paper presented at the IADC/SPE Drilling Conference, New Orleans, Louisiana, February SPE-59175-MS  
<https://doi.org/10.2118/59175-MS>
- Hanson, P.M., Trigg Jr., T.K., and Rachal, G., et al., 1990. “Investigation of Barite “Sag” in Weighted Drilling Fluids in Highly Deviated Wells,” Paper presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, September  
<https://doi.org/10.2118/20423-MS>
- Troncoso, J., Slater, K., and Jaimes, JP., 2018. “Barite Sag Measurements Using a Portable Dynamic Flow Loop,” AADE Fluids Technical Conference and Exhibition.  
<https://www.aade.org/application/files/2115/7131/7045/AADE-18-FTCE-048 - Troncoso.pdf>
- Zamora, M., 2011. “Taming of the Shoe,” AADE National Technical Conference and Exhibition. Houston  
<https://www.aade.org/application/files/8115/7261/8788/AADE-11-NTCE-44.pdf>
- Zeng, W. and Bouguetta, M., 2016. “A Comparative Assessment of Barite SAG Evaluation Methods,” Paper presented at the SPE Deepwater Drilling and Completions Conference, Galveston, Texas, September SPE-180348-MS  
<https://doi.org/10.2118/180348-MS>