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THE EFFECT OF SHEARING ON BARITE SAG

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ABSTRACT

Sag of weight material is an oil or geothermal well drilling phenomenon that is difficult to determine from industry standard measurements. To create a sag free fluid, it is necessary to create a structure in the fluid even though it is in a liquid state. Thus, the elastic responds must be larger than the energy loss responds in the fluid. This is possible in a water-based drilling fluid, but not in an oil-based fluid. Oil-based fluids is a combination of a multimodal dispersion and an emulsion. There are no real gels formed in an oil-based drilling fluid. The fluid is thickened by having Brownian motion to develop a geometrical structure of water droplets or solid particles. Adding barite to a drilling fluid will increase the density and also bring more particle with a huge surface area and thus viscosify the fluid.

Sag in water-based drilling fluids has its highest severity at 1.55 sg. However, because of the nature of polymers in water-based drilling fluids, sag is not a problem as long as the polymers are well dispersed. For higher densities the sagging barite particles float up on the material creating a counterflow helping to disperse the barite. The situation is more complex for oil-based drilling fluids. There are normally no real networks creating a real yield stress or a real gel structure. The viscosity is constructed by adding emulsified water with additives working in the oil-phase between the water droplets.

Because of the size of the barite, the oilfield viscometer size is constructed with a gap somewhat larger than 1mm to provide viscosity data relevant for frictional pressure losses in the drill pipe and in the annulus. As mentioned above barite act like a viscosifier in addition to act as a weighting agent. Thus, sag cannot be determined by the properties of the fluid m being much larger than the barite particle volumes. The interesting parts controlling the sag is likely to be due to the droplet emulsion as it forms the fluid volume relevant for the barite.

If the drilling fluid is sheared properly, both the droplet size and the interdroplet distances are reduced. The barite particle size has not been changed. But the barite particle cannot move without creating a flow making a collision between water droplets. Even though it is not measured on viscosity measurements made in accordance with standards, this increases the viscosity significantly seen from the individual barite particles. Hence, sag can be reduced by shearing.

INTRODUCTION

Barite sag is a phenomenon that is challenging, or sometimes impossible, to detect using industry standard measurements[1,2]. It has been suggested that to create a sag free fluid, the fluid must develop a structured network even when it is in a liquid state. In other words, the fluid's elastic modulus, G', should exceed the energy loss modulus, G'' also when being subject to shear. This condition can be achieved in water-based drilling fluids, but is generally not possible in oil-based fluids. Oil-based drilling fluids do not form true gels; instead, they thicken due to Brownian motion creating a geometrical structure of water droplets and solid particles. Adding barite increases the drilling fluid's density, but it also introduces a large number of particles with extensive surface area. This makes barite act as a viscosifier as well as a weighting agent. This is illustrated in **Fig. 1** which is based on data from Halvorsen et al.[3] who measured Herschel-Bulkley parameters as function of density for an oil-based drilling fluid. The Herschel-Bulkley model is used here with dimensionless shear rates, indicating that the drilling fluid's viscosity is proportional to the sum of its yield stress and excess stress at shear rates relevant to drilling operations, divided by the relevant shear rate[4] as shown in Eq. 1.

$$\tau = \tau_y + \tau_s \left(\frac{\dot{\gamma}}{\dot{\gamma}_s}\right)^n \tag{1}$$

where τ_y is the yield stress, τ_s is the additional stress or surplus stress at the typical flow shear rate, $\dot{\gamma}_s$, $\dot{\gamma}$ is the actual shear rate and *n* is the flow index. As illustrated in **Fig. 1**, the yield stress of the drilling fluid exhibited a gradual increase with the addition of barite. At a shear rate of 170 s^{-1}, representative of conditions encountered when drilling 8½″ sections, the corresponding shear stress increases to an even greater extent than the yield stress alone. This additional contribution, referred to as the surplus stress, becomes increasingly pronounced as barite concentration rises, whereas the flow index, or curvature index remains largely unaffected. The shear stress at 170 s^{-1} can therefore be obtained by summing the yield stress and the surplus stress, as expressed in Eq. 1[5].

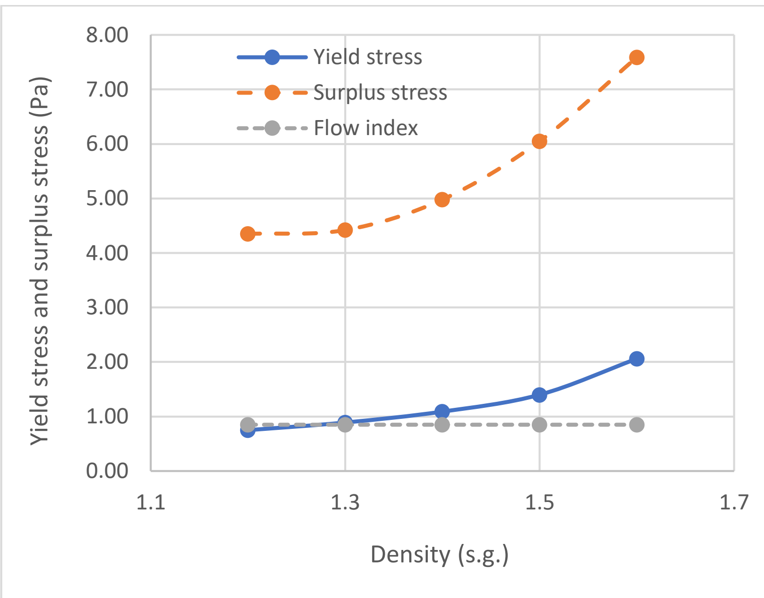

FIGURE 1: Barite as viscosifier in an oil-based drilling fluid. Data based on Halvorsen et al.[3]

The Bingham plastic model as defined in API and ISO procedures[6,7], does not provide sufficiently accurate viscosity estimates in the low shear-rate regime that is critical for evaluating barite sag[2]. In contrast, the Herschel–Bulkley model provides a reasonable approximation of drilling-fluid viscosity across a broad range of shear rates and is therefore widely applied in hydraulic pressure-loss calculations. Because the model is strictly empirical and have only limited relations to internal structures in the fluids, it cannot simultaneously reproduce accurate viscosity values for hydraulic calculations and for improving fluid stability. The low shear-rate yield point (LSYP), as defined by Zamora and Power and incorporated into API specifications[8,6], offers a practical approximation of the yield stress for use in pressure-loss predictions. The LSYP is calculated as $\tau_y = 2\tau_3 - \tau_6$, where $\tau_3$and $\tau_6$correspond to dial readings at 3 and 6 rpm on a standard rotational viscometer. Although this parameterization is adequate for hydraulic modeling, the following analysis demonstrates that LSYP-based values are insufficient for determining the rheological characteristics required to prevent barite sag.

The yield stress of a complex fluid cannot be represented by a single, well-defined value. Rønningsen[9], in his analysis of the rheology of waxy crude oils, describes the yielding process as a sequence of distinct deformation regimes: *"When subjected to a given shear stress, the rheological response is characterized by an initial, transient elastic deformation, followed by a creep flow period at very low shear rate, the length of which depends on the shear stress, then a fairly rapid collapse of the gel towards an equilibrium shear rate, characteristic for a given temperature"*. This behaviour illustrates that flow initiation does not occur instantaneously. Instead, yielding begins only once the applied shear stress exceeds a critical level, and the rate at which flow develops depends both on the magnitude of the applied stress and on the microstructural characteristics of the fluid. Consequently, startup flow may proceed gradually or abruptly, depending on the fluid composition and the imposed stress conditions.

SAG IN OIL-BASED DRILLING FLUIDS

Sag in water-based drilling fluids reaches its maximum severity at a density of approximately 1.55 sg[2]. At higher fluid densities, the settling barite particles induce a counter-flow of the continuous phase, which enhances barite dispersion and mitigates further sag. In water-based systems, the presence of well-dispersed polymers generally prevents significant sagging, as these polymers establish sufficient structural integrity to stabilize the suspension.

The behaviour of oil-based drilling fluids is more complex. These systems typically lack a true three-dimensional network capable of generating a substantial yield stress effect or a robust gel structure. Instead, their viscosity arises primarily from internal placement of emulsified water droplets and the action of oil-phase additives that interact within the continuous oil medium.

Because barite particles and fluid loss additives are relatively large, oilfield viscometers are designed with a measurement gap of 1.17 mm to ensure that the recorded rheological properties reflect frictional pressure losses in both the drill pipe and the annulus. As noted previously, barite functions not only as a weighting material but also contributes to the apparent viscosity of the fluid. Consequently, sag cannot be reliably assessed using rheological measurements obtained at measurement volume scales significantly larger than the characteristic barite particle size.

A key factor influencing sag behaviour is likely the droplet emulsion, since the barite particles are suspended within the continuous oil phase that contains dispersed water droplets.

The barite therefore experiences a two-phase flow environment in which the suspended solids interact with a fluid microstructure composed of elements significantly smaller than the barite itself. For a typical oil-to-water ratio of approximately 80/20 and a reasonably uniform droplet size distribution, the mean spacing between water droplets will be on the order of the droplet diameter. This geometrical observation is independent of the absolute droplet size.

Omland[10] presented an electron microscopy image of an unsheared oil-based drilling fluid showing water droplets approaching 100 µm in diameter (**Fig. 2**), illustrating the variation in the scales of the emulsion structure that governs barite suspension behaviour.

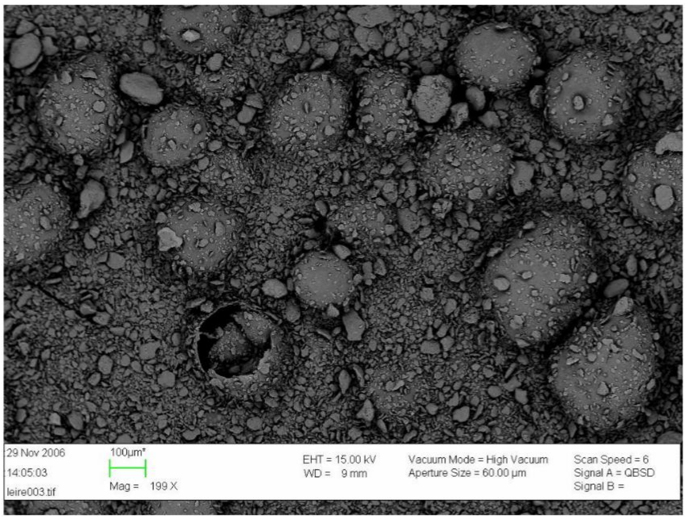

FIGURE 2: Example of a nearly un-sheared oil-based drilling fluid[10]. Courtesy of T.H. Omland

In the illustrative example shown in **Figs. 3–4**, an unsheared drilling fluid contains numerous barite particles whose D_{50} values are comparable to, or smaller than, the emulsion droplet size. Under these conditions, many barite particles encounter relatively unobstructed oil channels between the large droplets, allowing them to settle rapidly through the continuous phase (**Fig. 3**). In such a system, the only mechanism resisting sag is the viscosity of the base oil itself.

Referring to the fluid sample shown in **Fig. 2**, if the emulsion droplet size approaches 100 µm, then all barite particles in a standard API barite particle size distribution would be prone to settle. This effect is anticipated as the emulsion microstructure expectedly provides insufficient hindrance to the barite particles downward migration. It is necessary to comment that this tendency of all barite particles sagging down is modified also by other phenomena. For barite particle sizes close to 5 micron, the settling speed due to gravity becomes equal to the particle speed caused by Brownian motion. Furthermore, several oil wettable additives are introduced in the oil phase, such as organophilic clays and oil wetting surfactants, and sometimes polymeric materials. Thus, it is the larger barite particles that may be prone to sag if the internal fluid properties are not designed to sufficiently prevent this.

When the emulsion in the drilling fluid illustrated in **Fig. 3** is subjected to sufficient shear, the water droplets are reduced in size, as depicted in **Fig. 4**. This reduction decreases the inter-droplet spacing, which becomes comparable to the new, smaller droplet diameter. The barite particle size, however, remains unchanged by the shearing process. Under these conditions, the barite particles that previously settled freely through the large droplet network in **Fig. 3** can no longer move without creating frequent collisions with the dispersed water droplets. These droplets, in turn, also interact with one another, producing localized rearrangements and occasional leapfrogging behaviour. Collectively, these interactions substantially increase the effective internal viscosity as experienced by the barite particles. Thereby, this phenomenon markedly reduce sag even though the viscosity of the bulk drilling fluid creating the frictional pressure loss for the annulus flow can remain unchanged.

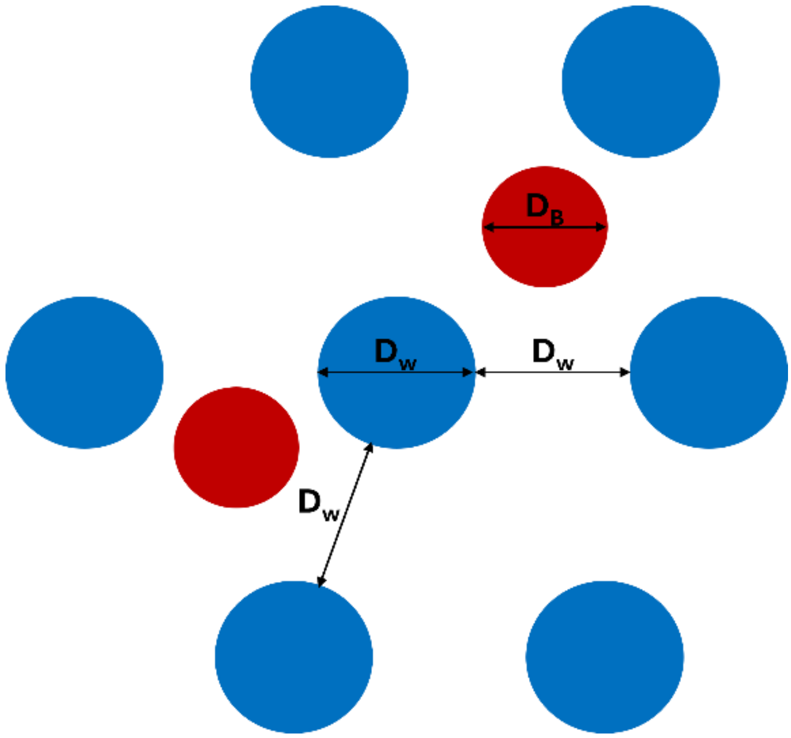

FIGURE 3: Illustration of a nearly un-sheared oil-based drilling fluid emulsion with oil-water ratio around 80/20 (blue particles are water droplets) with one similar size barite particle (red particles)

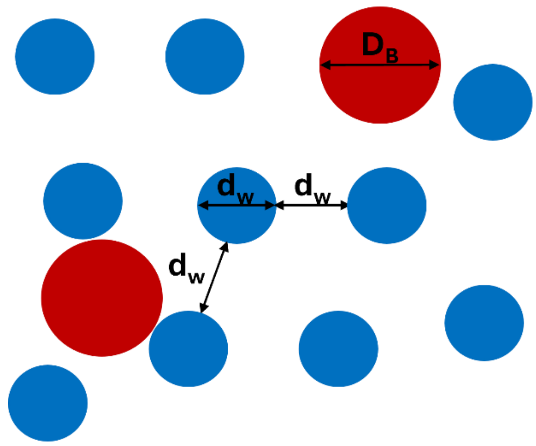

FIGURE 4: Illustration of a sheared oil-based drilling fluid emulsion with oil-water ratio around 80/20 (blue particles are water droplets) with barite particles of the same size as illustrated in **Fig. 3** (red particles).

Field experience clearly demonstrates that applying sufficient shear to a drilling fluid reduces its tendency to exhibit barite sag[10,11] for the time period where the droplet distribution remains stable. In a shear test conducted at a drilling-fluid plant, a 25 m³ premix was subjected to intensive shearing. Although no measurable change in filtrate viscosity was detected using the standard rheological procedures provided by API, the electrical stability (ES) increased markedly. This rise in ES indicates that the emulsion droplets were broken into smaller droplets, which experience greater hydrodynamic resistance when moving through the base oil to bridge off the electrical circuit in the ES measurements. Such microstructural refinement is therefore expected to significantly diminish barite sag[11].

PROPERTIES OF OIL-BASED DRILLING FLUIDS

Most introductory fluid-mechanics texts include a brief discussion of the characteristic length scales required for continuum descriptions of fluid flow. Batchelor's *An Introduction to Fluid Dynamics*[12] is no exception. In his treatment, he presents measurements of fluid density for a simple Newtonian fluid as a function of the sample volume to which the measuring instrument responds. For a large such volume the density may vary because of natural variations of spatial distribution of density. When this volume becomes sufficiently small, a constant density is obtained representing the local value of fluid density. For even smaller volumes measured the measured density begins to fluctuate due to molecular-scale variations, illustrating the breakdown of the continuum approximation at very small length scales.

For an oil-based drilling fluid the situation becomes less predictable. Measurable variations in density, along with variations in viscosity and other properties arise at fluid volumes far larger than those at which molecular-scale fluctuations appear in simple liquids. This behaviour is illustrated in **Fig. 5**. An oil-based drilling fluid comprises a heterogeneous mixture of emulsified brine in a base oil, organophilic clays or polymers, barite, and several additional additives. The relevant characteristic length scale is on the order of ten times the diameter of the largest barite particles. When API-grade barite is used, this requirement yields a representative element volume corresponding to a spherical volume with diameter of approximately 0.70 mm, below which the fluid can no longer be assumed to exhibit uniform properties.

Figs. 5 and 6 provide an illustration of this effect. As the measurement volume is progressively reduced along the trajectory indicated by the boxes in the diagonal in **Fig. 5**, a corresponding density response illustrated in **Fig. 6** is obtained. Even so, the density variations observed here occur at volumes several orders of magnitude larger than those reported by Batchelor[12] for simple fluids, reflecting the much coarser microstructural heterogeneity inherent to oil-based drilling fluids. In addition to density, similar effects caused by the measurement volume will be found for other properties like rheological parameters.

A consequence of using the simplified representation shown in **Fig. 5**, the flow behaviour of an oil-based drilling fluid is most appropriately interpreted within the framework of multiphase or multicomponent flow. For the larger barite particles, stability depends on their interaction with a surrounding mixture composed of droplets and smaller solid components that are orders of magnitude smaller than the barite itself. When the characteristic barite size approaches that of the surrounding dispersed entities, a multicomponent flow description may be required.

In such cases as described in the previous sections, constitutive models developed for suspensions using physical framework, such as the Quemada model[13,14,15,16], may offer a more useful starting point than applying empirical models based on curve fitting viscosity data. With suitable modification or extension, a model should potentially be adapted to describe barite sag under conditions where particle–droplet and particle–particle interactions dominate the suspension rheological performance.

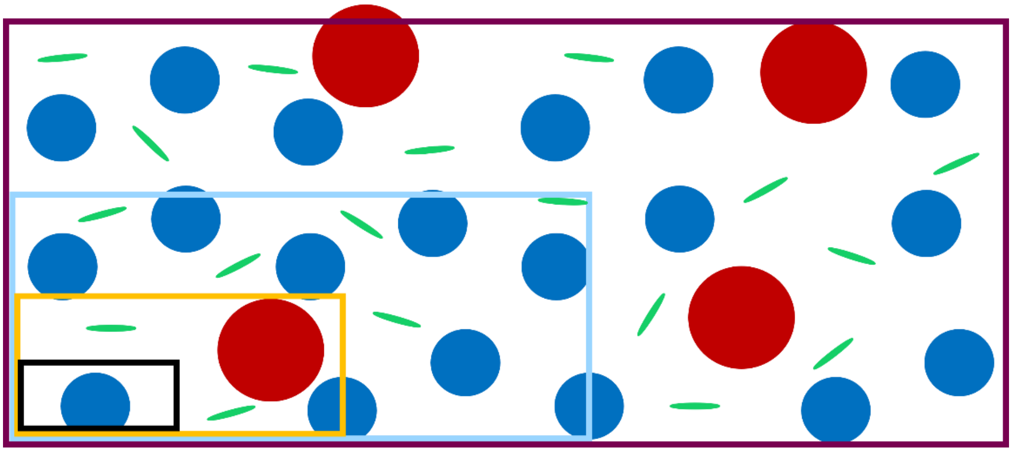

FIGURE 5: Illustration of a simplified oil-based drilling fluid composition (blue particles are water droplets) with one size barite particles (red particles) and other additives (green bars). The squares show the volumes of fluid to which the measurements belong. The volumes vary in size along the diagonal.

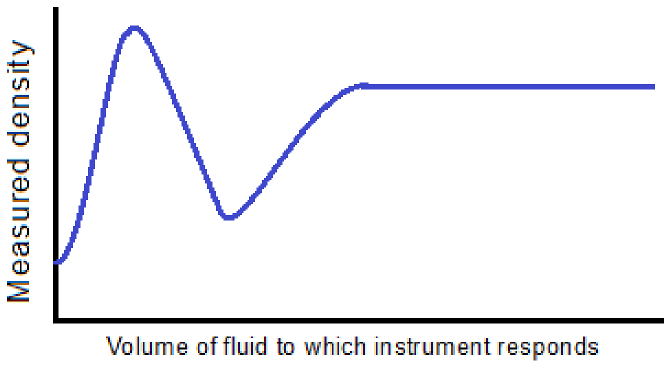

FIGURE 6: Example of an oil-based drilling fluid density as function of the measurement volume

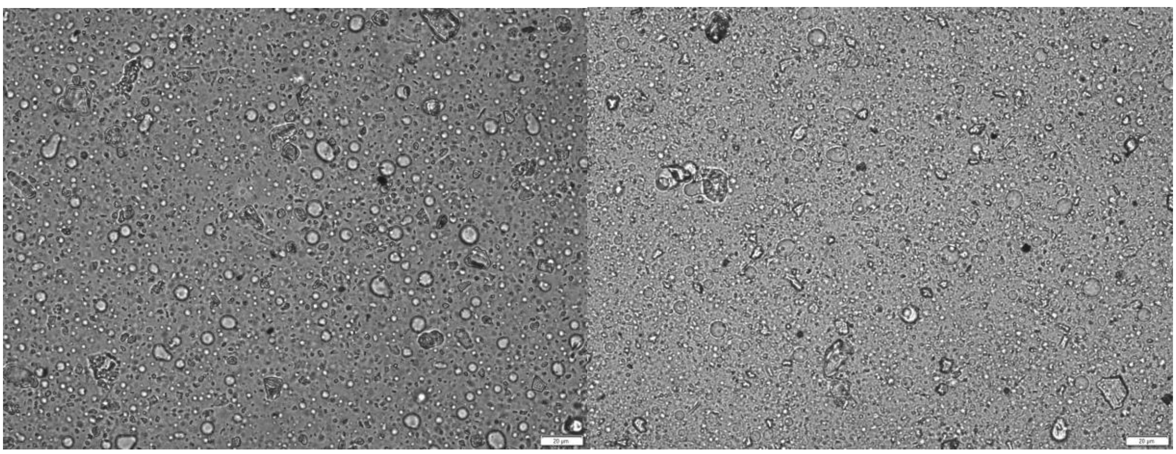

FIGURE 7: Un-sheared oil-based drilling fluid premix (no Barite) to the left and sheared premix to the right. Measurement bar length is 20 micron.

The viscometer specified by API requirements[6] is designed to generate rheological data appropriate for pressure-loss calculations. It operates using a rotating-cylinder geometry in which the sample is contained within a measurement cup, following the classical configuration described by Whorlow[17]. To ensure valid continuum-scale measurements, the gap between the cylinders must be at least an order of magnitude larger than the largest suspended particles. For drilling and wellbore fluids, these largest particles are typically on the order of 75 µm, necessitating a gap width exceeding 1 mm.

Because of the large measurement gap in oilfield viscometers, viscosity values obtained from such instruments cannot be expected to reflect the stability of fluids whose governing flow phenomena occur at much smaller length scales within the microstructure. In common well circulated oil-based drilling fluids, emulsion droplets typically fall within the 5–10 µm range, as illustrated in **Fig. 7** for diluted samples. Consequently, API-type viscometers probe a volume far too large to capture the microstructural interactions that control barite suspension and sag behaviour.

SUMMARY

Barite sag in oil-based drilling fluids arises from interactions within a multiphase system composed of barite particles, emulsion droplets, and base oil. Because barite particles are much larger than the surrounding droplets, their stability depends on how effectively the smaller dispersed phases hinder particle settling. When droplet sizes are large or insufficiently sheared, barite can move through free oil channels and sag rapidly. Proper shearing reduces droplet size and thus spacing without destroying other typical oil-based drilling fluid components (with the exception of calcium carbonate), increasing hydrodynamic resistance and creating a more complex multiphase flow environment that significantly suppresses barite sag. These internal flow effects cannot be monitored using viscosity measurements in accordance with API requirements.

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