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Drilling Fluid Selection to Minimize Formation Invasion - A New Test Method

Tatiana Hoff, Robert O'Connor and Fred Growcock, MASI Technologies *LLC* and M-I SWACO

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Abstract

Core Leak-Off tests are commonly used to determine the ability of a drilling fluid to seal permeable formations at downhole temperature and pressure. Unfortunately, the complexity, time and cost to run these laboratory tests make it highly desirable to find a simpler, faster and more economical test that can serve as an accurate predictor of the ability of a fluid to control invasion into a formation.

The Capillary Suction Time (CST) Test, a rapid and cost-effective technique, is used to ascertain the state of flocculation of a fluid and its ability to control filtration through permeable media. The standard CST method breaks down, however, for highly dispersed low-filtration-rate fluids. In this study, a Modified CST procedure was developed that eliminates this problem and is shown to provide results that correlate well with conventional static Core Leak-Off test results for drilling fluids. This procedure calls for measurement of the travel distance of the fluid front, or Capillary Suction Distance (CSD), in a specified amount of time.

For drilling fluids that seal via similar mechanisms, the Modified CST Test can be used to predict the trend in the rate of fluid invasion into permeable formations. Fluids which seal via different mechanisms yield different CSD vs Leak-Off correlations, most likely because of differences in spurt-loss behavior.

Introduction

Core Leak-Off tests are commonly used to ascertain the ability of a drilling fluid to seal permeable rock under downhole conditions. Unfortunately, these tests are expensive and require a long time to set up. To monitor fluid invasion trends and to evaluate potential treatments for reducing fluid invasion on location, a simpler screening test is highly desirable.

The Capillary Suction Time (CST) Test has been used since the 1970's as a fast, yet reliable, method for characterizing fluid filterability and the condition of colloidal materials in water treatment facilities and drilling fluids. For the latter, it has usually been applied to determine the state of flocculation of clay-bearing fluids and to screen potential shale inhibitors. In this work, the CST method was evaluated as a screening tool for predicting relative invasion rates of drilling fluids in permeable cores.

However, most of the drilling fluids examined that are designed to generate low fluid loss gave CST values that were so high that the invasion came to be dominated by experimental artifacts, such as fluid evaporation. This necessitated modifying the CST procedure so as to minimize artifacts and permit differentiation of the fluids under investigation.

Subsequently, several types of drilling fluids were subjected to conventional static Leak-Off tests and Modified CST tests. These included gel-based, reservoir, mixed metal and aphron drilling fluids. For some of these fluids, the effect of fluid composition was also examined.

Experimental Approach

The Modified CST and Core Leak-Off test methods utilized in this project are described in Appendices A and B at the end of this report. In all cases, the fluid samples were blended with a Prince Castle mixer and hot-rolled for 16 hours at 150°F.

Initial tests were performed using the standard CST method.[1] Various mud types were evaluated, and the results are given in Figure 1.

The fluids with very long CST values cannot be very clearly differentiated, and artifacts such as evaporation of water from the blotting paper control the rate of advance of the filtrate. It was determined that CST

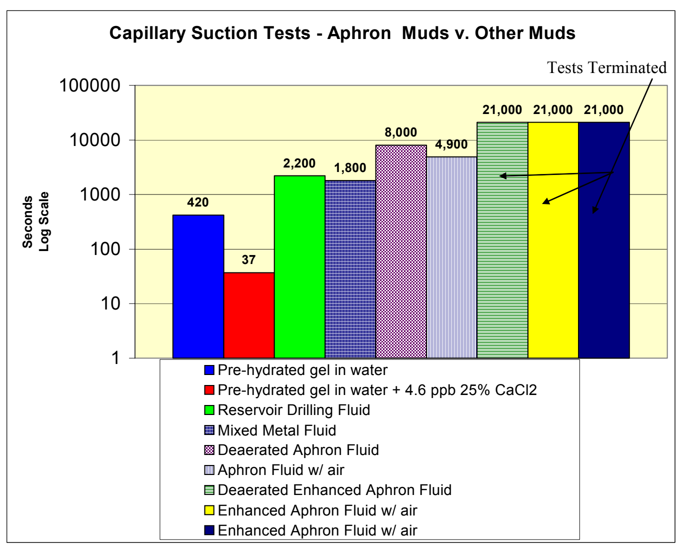

Fig. 1 - CST Results - Standard CST Procedure.

values higher than a few thousand seconds are fraught with unacceptably high error. For these fluids, the Modified CST test appears to provide a much more precise and accurate way to monitor relative filtration rates. As described in Appendix A, the Modified CST test involves measuring CSD, the distance in mm traveled by the fluid in a given time period. Results for the Aphron Drilling Fluid (with and without entrained air) appear in Table A1 in Appendix A.

Four samples of each system were blended, and the concentration of viscosifier specific to each system was varied. The systems utilized were: an Aphron Drilling Fluid (ADF), an Enhanced Aphron Drilling Fluid (Enhanced ADF), a Reservoir Drilling Fluid (RDF), and a Mixed-Metal Drilling Fluid (MMDF). These samples were run as "solids free" systems, but some tests were also run with samples containing 30 lb/bbl of $CaCO_3$ with a nominal particle diameter of 40 μm. The corresponding Low-Shear-Rate Viscosity (LSRV), Leak Off, and CSD were measured for each one of these samples. All of the tests were run at room temperature. LSRV was measured with a Brookfield LV-II+ Viscometer at 0.06 sec^{-1} using a L3 spindle. The Core Leak-Off tests were run with 1,000 psi confining pressure, 500 psi inlet pressure and no back pressure, using 2-in. long Aloxite cores of about 5-Darcy air permeability. In all cases, the CSD values used for the correlations were those measured at 60 min (half of the total testing time). The CSD vs Leak-Off correlations obtained with the 30-min CSD data were similar to these, but the CSD data appeared to be somewhat less precise. The correlations obtained with the 90-min and 120-min data were also similar to those obtained with the 60-min data and did not appear to provide any greater precision. Consequently, the 60-min CSD values were used for all of the correlations.

Filtration in the Modified CST (CSD) Test

"Static filtration takes place when the mud is not circulated, and the filter cake grows undisturbed." [2]

If a unit volume of a stable suspension of solids is filtered against a permeable substrate (paper or core in our case), and x volumes of filtrate are expressed at time t, then $1 - x$ volumes of cake will be deposited on the substrate. As a simplifying approximation, the rate of growth of the filter cake is assumed to be proportional to the rate of growth of filtrate. Therefore, if Q_c represents the volume of the cake, and Q_f the volume of the filtrate:

$$\frac{Q_c}{Q_f} = \frac{1-x}{x} = R \qquad \text{(Eq. 1)}$$

where R is a constant ratio of filter cake to filtrate. The area of the filter cake, A, is constant in linear static filtration, such as API Fluid Loss and Core Leak-Off tests. It is also constant in a CSD test, though the filtrate itself expands radially along the plane of the paper. Q_c is given by the product of A and the thickness of the filter cake:

$$Q_c = A \cdot h \qquad \text{(Eq. 2)}$$

Thus,

$$h = \frac{R \cdot Q_f}{A} \qquad \text{(Eq. 3)}$$

Now, Darcy's law states

$$\frac{dq}{dt} = \frac{k \cdot \Delta P \cdot A}{\mu \cdot h} \qquad \text{(Eq. 4)}$$

Where k = permeability of the filter cake (Darcy), ΔP = differential pressure across the cake (atm), μ = viscosity of the filtrate (cP), h = thickness (cm), q = volume of filtrate (cm^3), and t = time (sec).

Therefore,

$$\frac{dq}{dt} = \frac{k \cdot \Delta P \cdot A^2}{\mu \cdot R \cdot Q_f} \qquad \text{(Eq. 5)}$$

Integrating,

$$Q_f^{\ 2} = \frac{2k \cdot \Delta P \cdot A^2 \cdot t}{\mu \cdot R} \qquad \text{(Eq. 6)}$$

Unifying the constant terms results in

$$Q_f^{\ 2} = K \cdot t \qquad \text{(Eq. 7)}$$

or,

$$Q_f = K' \cdot t^{1/2} \qquad \text{(Eq. 8)}$$

Where K and K' are proportionality constants. Equation (8) governs filtration under static conditions.[2]

In the Modified CST method (CSD), the distance that the fluid travels, d, is proportional to Q_f. Thus,

$$d = K'' \cdot t^{1/2} \qquad \text{(Eq. 9)}$$

Some results for two types of Aphron Drilling Fluids are plotted in this fashion in Fig. 2. The results in Fig. 2 for the two samples of Deaerated Aphron Drilling Fluids demonstrate the reproducibility of the Modified CST test.

The linearity of the $t^{1/2}$ plots shows that CSD follows static filtration theory. It does not necessarily follow, however, that CSD will correlate with core Leak-Off behavior. Key differences between core Leak-Off and

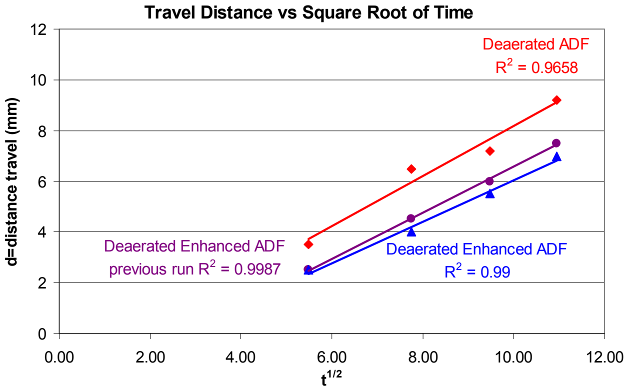

Fig. 2 - CSD vs. Square Root of Time.

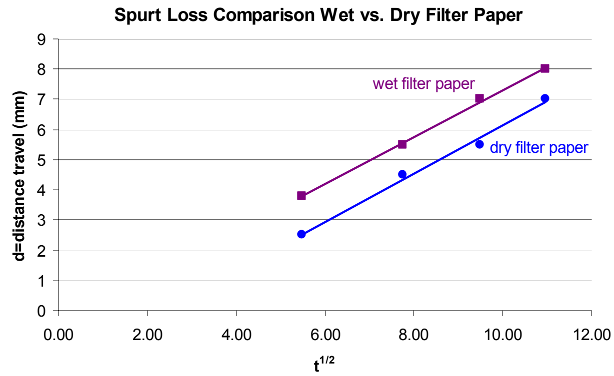

Fig. 3 - CSD for Wet vs. Dry Filter Paper Deaerated Enhanced ADF.

Modified CST tests include saturation of the pore network (wet vs dry), the nature of the filter medium (core vs paper), differential pressure (elevated inlet pressure vs ambient pressure), and possibly temperature.

The effect of saturation of the pore network with the base fluid is manifested as a displacement in the apparent "spurt loss." Spurt loss is generally defined as the loss of whole mud that occurs initially during fluid invasion, i.e. prior to formation of a fully established filter cake. This is given approximately by the y-axis intercept on the $t^{1/2}$ plot. In the mathematical treatment of static filtration given above, spurt loss is assumed to be negligible. However, spurt loss is known to be significant in permeable rocks. Furthermore, "a low fluid loss and a dry cell with high hold up volume will cause a negative y-axis intercept".[3] To prove this, two CSD tests were run, one using dry filter paper and one using wet filter paper. The system used was Deaerated Enhanced Aphron Drilling Fluid with 5 lb/bbl viscosifier. The results are shown in the Fig. 3.

It is evident from Fig. 3 that, when the paper is saturated with water at the start of the test, the straight line plot for the dry filter paper is displaced upwards about one unit. The spurt loss changes from negative to approximately zero, thus confirming the role played by the interstitial fluid in the paper.

The effects of the nature of the filter medium and differential pressure are more complex. Once a filter cake is well established on a filter medium, the filtration rate is not expected to be affected very much by the nature of the filter medium (paper vs core), since fluid flow is controlled entirely by the permeability of the cake. Conversely, spurt loss is dominated by Darcy flow as in Eq. 4, where k and h are the permeability and thickness of the filter medium, respectively, and μ is the viscosity of the whole mud. Each mud system has a different viscosity profile, which will in turn produce a different rate of spurt loss. In addition, different concentrations and size distributions of particulate matter in the mud will affect the spurt loss period (the length of time of the spurt loss phase). Thus, total spurt loss, as given by the product of the spurt loss rate and spurt loss period, will vary from mud to mud. The higher the permeability of the filter medium, the greater will be the spurt loss and the variability in spurt loss from mud to mud. Thus, the effects of the nature of the filter medium and pressure differential are expected to be manifested in a higher spurt loss for the Core Leak-Off tests vs the CSD tests. This will undoubtedly lead to different correlations of Core Leak-Off vs CSD for each mud system,[4,5] as demonstrated in the following section.

Results

The results for all of the Modified CST (CSD) and core Leak-Off tests are shown in Table A2 (see Appendix).

Correlations of CSD and Core Leak-Off vs. LSRV

The effect of LSRV on CSD (see Table A2) is shown in Fig. 4. All of the curves in Fig. 2 follow power law trends fairly well, though it appears that the curves cannot be unified into a single model, *i.e.* each fluid system appears to follow a different power law expression. The ADF systems give lower CSD values than the MMDF and RDF systems. Aerating the Enhanced ADF system lowers the CSD even more. This

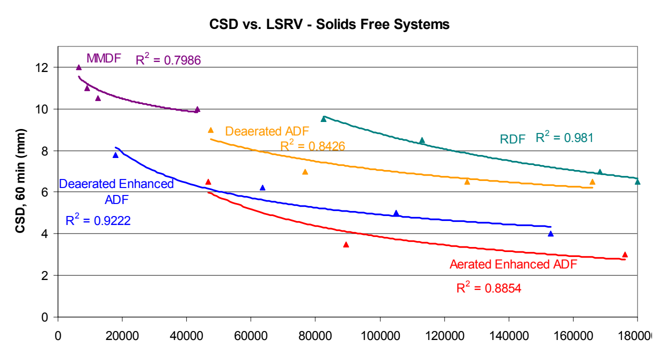

Fig. 4 - CSD vs. LSRV for All the Systems.

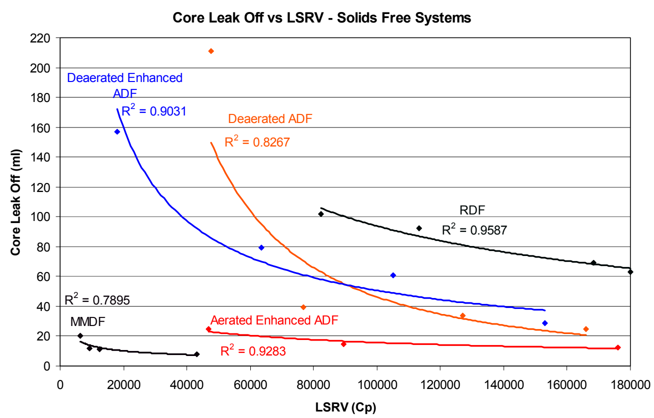

Fig. 5 - Core Leak-Off vs LSRV.

is likely the result of the air acting as a bridging agent. The air in all ADF systems is present in the form of pressure-resistant bubbles called aphrons, which have been shown to function as an invasion control agent.[6]

Fig. 5 shows the correlation of Core Leak-Off vs. LSRV for all the data. As was the case for the CSD correlations, Core Leak-Off appears to follow a power law trend with respect to LSRV. Again, it does not seem possible to be able to unify the curves; indeed, the curves appear to be considerably more scattered than were the CSD vs LSRV curves (Fig. 4). As discussed in the previous section, this is likely the result of spurt loss being more variable for invasion into a core than for invasion into blotter paper. This is especially evident for MMDF, which exhibits the lowest Core Leak-Off, yet the highest CSD. The sealing mechanism of this fluid involves a special polymer-clay network that is thought to be particularly effective at reducing spurt loss.[7]

Core Leak-Off vs. CSD

Fig. 6 shows the correlation of Core Leak-Off vs. CSD for all the systems. As expected from previous discussions and borne out by Fig. 6, there is a fair correlation between CSD and Core Leak-Off for individual fluid systems, but there is no unifying

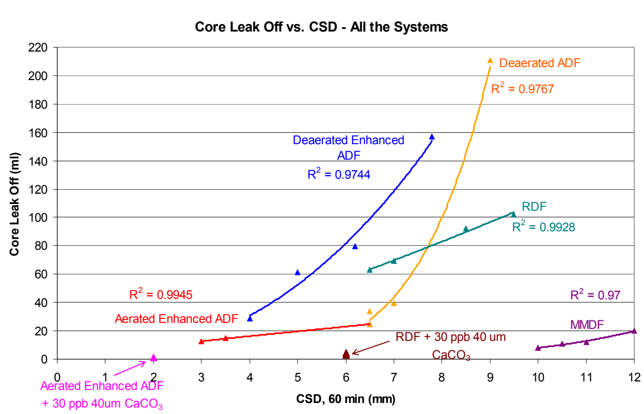

Fig. 6 - Core Leak-Off vs CSD.

correlation curve for all of them.

Addition of $CaCO_3$ to the RDF and the Enhanced ADF systems reduces both Leak-Off and CSD. Likewise addition of air to the Enhanced ADF system reduces both Leak-Off and CSD.

From the results shown in Fig. 6, it appears that CSD and Core Leak-Off for any given fluid system correlate well enough to approximate the value of the Leak-Off of a particular system based on its CSD value.

Thus, the value of CSD measurements is expected to lie in monitoring of fluid invasion trends and evaluation of potential additive treatments.

Summary

Using a Modified CST procedure that generates a measurement of CSD (the distance that the fluid front travels in 60 min), it has been demonstrated that CSD for low-fluid-loss drilling fluids correlates with Core Leak-Off test results and obeys standard static filtration theory. The Modified CST procedure has promise as an on-site tool to monitor fluid invasion trends and evaluate potential treatments for reducing fluid invasion.

The Aerated Enhanced Aphron Drilling Fluid and Mixed-Metal Drilling Fluid generate lower CSD and Core Leak-Off values than solids-free Aphron and Reservoir Drilling Fluids. Because the sealing mechanism varies with type of drilling fluid, different CSD vs Core Leak-Off correlation curves must be used for each fluid system. System-to-system variability of the CSD vs Core Leak-Off correlation is likely due to the greater impact that spurt loss has on Core Leak-Off than on CSD.

For a given drilling fluid system, CSD and Core Leak-Off correlate inversely with LSRV, *i.e.* CSD α $(LSRV)^{-1}$. In addition, additives such as $CaCO_3$ (and air in the Enhanced Aphron Drilling Fluid) decrease Core Leak-Off and, to a lesser extent, CSD.

Acknowledgments

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Nomenclature

ADF = *Aphron Drilling Fluid*
BHT = *Bottom-Hole Temperature*
CSD = *Capillary suction displacement (distance traveled by the fluid front)*
CST = *Capillary suction time*
LSRV = *Low-shear-rate viscosity at 0.06* sec^{-1}
MMDF = *Mixed Metal Drilling Fluid*
RDF = *Reservoir Drilling Fluid*
A = *Area of the filter cake* (cm^2)
d = *Distance that the fluid travels (mm)*
h = *Thickness (cm),*
k = *Permeability of the filter cake (Darcy),*
K & K' = *Proportionality constants.*

μ = *Viscosity of the filtrate (cP),*
ΔP = *Differential pressure across the cake (atm),*
q = *Volume of filtrate (cm3)*
Q_c = *Volume of the filter cake*
Q_f = *Volume of the filtrate:*
R = *a constant.*
t = *Time (sec).*
x = *Volume fraction of filtrate at time t*

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APPENDIX A - Modified CST (CSD) Procedure

For fluids with very long CST's – typically more than a few minutes for the fluid to travel between the two conducting rings – the distance traveled from the sample cup within an arbitrary time period (30, 60, 90 and 120 min was used in this work) provides an accurate relative assessment of the permeability of the filter cake:

- Two 2-cm (20-mm) rules are attached to the top of the transparent cover (see Figure A1).
- The 1.8-cm opening of the test cylinder is placed against the filter paper.
- Five mL of the test mud is placed into the cylinder using a 5-mL syringe.
- The migration of the mud fluid is recorded every 30 minutes for 2 hours.
- The results are expressed in distance (mm), or CSD, versus time (min). At least two readings from different points around the test cylinder are taken at each time and averaged.

Results obtained with a Deaerated ADF and an Aerated ADF are shown in Table 1. Sometimes the filtrate did not migrate uniformly in all directions, as noted by the ranges in CSD.

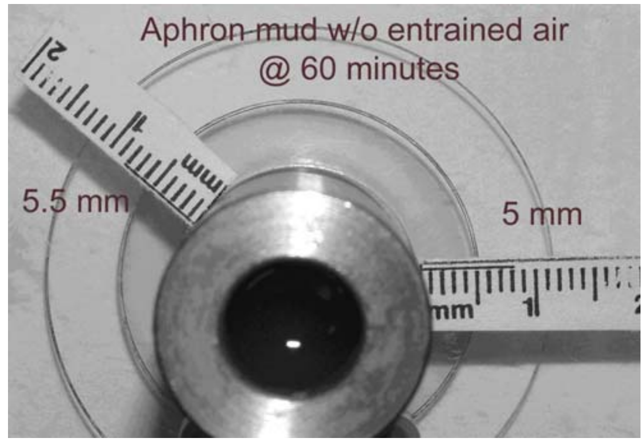

Fig. A1 - Modified CST (CSD) Apparatus.

Table A1 - Some Results of Modified CST Test

	Migration Distance CSD (mm from the outside of CST cylinder)			
Fluid	30 min	60 min	90 min	120 min
Deaerated ADF	2 - 3	5 - 5.5	6 - 7.5	7.5 - 8.5
Aerated ADF	2	3	3 -5	3 – 6

APPENDIX B -Leak-Off Test Procedure

The apparatus is shown in Fig. B1. The test procedure employs a constant Inlet Pressure of 500 psig and no back-pressure (Outlet Pressure of 0 psig) and is carried out at the same temperature as the CSD tests, i.e. ambient temperature:

- Heat oven to appropriate bottomhole temperature.
- Apply 500 psig to the piston port.
- Close off piston port (where 500 psig will still be active).
- Open confining port and apply 500 psig.
- Open piston port (both ports will be open at this point).
- Continue to apply pressure until it reaches 500 psig above hydrostatic pressure.
- Apply appropriate reservoir pressure (Back Pressure).
- Open computer program and begin to collect data.
- Apply appropriate mud pressure via accumulator while valve to seal tester is shut.
- Open mud pressure valve to seal tester to start test.
- Collect for 30 min.
- Release pressures in reverse order of application.
- Results are reported as leak-off (in grams) of fluid on a digital balance. This is converted to volume (mL) from the density of the leak-off fluid, the dead volume (water between core and mud sample) is subtracted, and the result is the net leak-off.
- % Invasion can also be calculated as

$$\frac{Pore\ \ Volume - Net\ Leak.Off}{Pore\ \ Volume} \bullet 100\%$$

Fig. B1 - Core Leak-Off Test Apparatus.

APPENDIX C

Table C1 - Summary of LSRV, CSD and Core Leak-Off Test Results

Drilling Fluid System	LSRV (cP)	CSD @ 60 min (mm)	Leak-Off (mL)
RDF			
Sample 1: 2.25 lb/bbl Viscosifier	82,382	9.5	101.8
Sample 2: 2.60 lb/bbl Viscosifier	113,200	8.5	92.2
Sample 3: 2.85 lb/bbl Viscosifier	168,400	7.0	69.3
Sample 4: 3.15 lb/bbl Viscosifier	180,000	6.5	63.1
MMDF			
Sample 1: 0.18 lb/bbl Polymer	6,400	12.0	20.3
Sample 2: 0.40 lb/bbl Polymer	9,200	11.0	11.8
Sample 3: 0.80 lb/bbl Polymer	12,400	10.5	11.0
Sample 4: 1.20 lb/bbl Polymer	43,200	10.0	7.9
Aerated Enhanced ADF			
Sample 1: 2.50 lb/bbl Viscosifier	46,800	6.5	24.5
Sample 2: 3.50 lb/bbl Viscosifier	89,600	3.5	14.9
Sample 3: 5.00 lb/bbl Viscosifier	176,000	3.0	12.4
RDF + 30 lb/bbl 40-μm $CaCO_3$			
Sample 1: 2.25 lb/bbl Viscosifier	62,387	6.0	2.9
Sample 2: 2.60 lb/bbl Viscosifier	168,800	6.0	4.4
Sample 3: 3.50 lb/bbl Viscosifier	206,400	6.0	4.1
Aerated Enhanced ADF + 30 lb/bbl 40-μm $CaCO_3$			
Sample 1: 5.0 lb/bbl Viscosifier	169,000	2.0	1.2
Deaerated Enhanced ADF			
Sample 1: 2.5 lb/bbl Viscosifier	17,996	7.8	156.8
Sample 2: 3.5 lb/bbl Viscosifier	63,586	6.2	79.5
Sample 3: 4.2 lb/bbl Viscosifier	105,000	5.0	61.0
Sample 4: 5.0 lb/bbl Viscosifier	153,000	4.0	28.8
Deaerated ADF			
Sample 1: 2.5 lb/bbl Viscosifier	47,590	9.0	210.8
Sample 2: 3.5 lb/bbl Viscosifier	76,784	7.0	39.6
Sample 3: 4.2 lb/bbl Viscosifier	127,000	6.5	33.9