



Innovation and Flexibility for Drill-in Fluids Design

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Abstract

Pressure-depleted reservoirs drilled with water-based fluid systems are subjected to high overbalance pressures due to drilling fluid densities greater than the density of water. Such overbalanced conditions are directly linked to lost circulation problems, stuck pipe and formation damage due to solids and fluid invasion.

Specialized technologies, such as under-balanced drilling with ultra-low density foams or aerated fluids, have been used to avoid most of the aforementioned problems;^{1, 2} however, high application costs have made these alternative systems almost prohibitive in many mature fields.

Proper selection of surfactants and polymers, together with the use of unique bridging material selection methods allow the design of highly thixotropic drill-in fluids that exhibit optimal filtration properties, excellent crude oil/drill-in fluids compatibilities and high return permeability.

This paper describes the development of a water-based drill-in fluid stabilized by a specially selected polymer-surfactant complex, containing bridging materials designed specifically for low pressured sandstone and carbonate reservoirs.

Introduction

In recent years, attempts have been made to develop low density drill-in fluid systems that eliminate reservoir intrusions by reducing the hydrostatic pressure across a production zone.³⁻⁵

A fundamental basis for the development of the new water-based drill-in fluid presented in this paper has been derived from studies conducted by the food and paint industries during the last decade, involving polymer-surfactant interactions.^{6, 7}

Previous industry publications have disclosed significant evidence demonstrating that certain surfactants, having a good association with polymers, form mixed micelles within a polymer-surfactant mixture, that produce gel structures in the aqueous phase while simultaneously decreasing interfacial properties (e.g.

the surface tension).⁶ In the case of modified polysaccharides and anionic surfactants, attractive interactions generate complexes characterized by micelles bound along the polymer chain.^{8, 9}

The net result of these complex surfactant-polymer associations, together with a proprietary blend of bridging particles, is a non-damaging drill-in fluid that minimizes fluid and particulate invasion for depleted sandstone and/or carbonate reservoirs. This paper summarizes the extensive laboratory testing used to validate the above claims.

Drill-in Fluid Design

Evaluations were conducted for water-based fluid formulations containing variations of specially selected surfactants and polymers in a 5% dispersed internal phase of nonpolar fluid. The formulations were prepared systematically, varying the concentrations in order to obtain high viscosity at low shear-rate with good API filtration control and generally high return oil permeability.

Evaluated components included surfactants with high hydrophilic nature, water-soluble polymers, modified biopolymers, and polymer-stabilizing preservatives for elevated circulating temperatures.¹⁰ The dispersed internal phase included a nonpolar fluid, such as high molecular weight polyglycol, synthetic base oil or mineral oil. Likewise, inorganic and organic pH buffers were selected that would not interfere with the surfactant-polymer interaction or dispersed organic phase. The following test matrix includes the most critical laboratory testing steps for fluid evaluation:

1. Rheological evaluation using a Fann 35A Viscometer, Brookfield Viscometer, and SR-5000 rheometer after heat aging up to 149 °C (300 °F).
2. Dynamic and static filtration using a Dynamic Filtration Device (DFD), Fann 90 equipment and Particle Plugging Apparatus (PPA).
3. Droplet size determination of the internal phase using a light-scattering technique with a Malvern Instruments Mastersizer.

4. Formation damage evaluation (return oil permeability) using a Hassler Cell Permeameter.
5. Compatibility testing between crude oil and the drill-in fluid.

Laboratory Results and Discussion

Polymer-Surfactant Selection

Polymer-surfactant combinations were initially selected based on a theory-based study involving several surfactants, modified biopolymers and synthetic polymers. Numerous laboratory tests were performed using a range of modified polymer and surfactant concentrations. The concentration of the polymer blend varied between 4.0 and 7.5 lb/bbl; and the concentration of the surfactant varied between 3.0 and 6.0 lb/bbl. Subsequent laboratory evaluations were made changing concentrations of various polymeric thermal stabilizers for a range of temperatures between ambient and 149°C (300°F).

Table 1 shows the rheological effects of varying the polymer and surfactant concentrations in formulations that also included 5% (v/v) synthetic base as an internal phase. The three formulations tested show low plastic viscosities, moderately high yield points and elevated, but non-progressive, 6 and 3 rpm Fann dial readings. Gel strengths were measured at 10-sec, 10-min, and 30-min intervals and the results also clearly demonstrate the non-progressive nature of the polymer-surfactant-oil interaction.

Table 1 shows that the polymer-surfactant blend generates very small olefin droplets in the internal water phase. These virtually non-compressible droplets function as a lubricant¹¹ and filtration control additive, and slightly reduces the density of the system.

A side effect (neither positive nor negative) of the polymer-surfactant interaction is the development of a 'mini-foam' with droplet sizes similar to the dispersed olefin. This phenomenon is typical for surfactant solutions where the surfactant possesses a high degree of hydrophilic nature. When foaming is undesirable, it can be controlled with defoamer additions.¹²

Evaluations of the formulations described in **Table 1** include low shear-rate viscosity, dynamic filtration, return permeability and fluid compatibility. Results of these evaluations are discussed below.

Drill-in fluid properties

The low shear-rate viscosity (LSRV) of each fluid formulation was measured between 0.3 rpm and 100 rpm using a Brookfield Viscometer. The results obtained (**Figure 1**) show a highly thixotropic behavior with viscosities around 100,000 cP at the lowest shear-rate. This high rheology value is a result of complexes formed by multiple associations between the long-chain polymer, the surfactant micelles and the dispersed oil phase.

Although the fluid has high viscosity at low shear rate, the Fann 35 data shows that the fluid viscosity is low in the high RPM ranges. These results suggest that the fluid viscosity will allow fluid passage during solids removal in the shale shaker equipment. This was an important criterion because solids control management is critical for all drilling fluid applications.

The viscoelastic properties of Formulation 2, reported in **Table 1**, were also measured with an SR5000 Rheometer. This device is used to determine the presence of three-dimensional continuous networks generated by the polymer-surfactant complexes within a gel structure. **Figures 2 and 3** show the viscoelastic properties of the fluid formulation, with and without solids contamination, hot rolled at 93.3°C (200°F). The results show that the elastic modulus (G') dominates the viscous modulus (G'') in the entire frequency region. Likewise, the viscous modulus and elastic modulus do not converge in the low angular frequency range. This behavior occurs only when a fluid possesses structured networks similar to those produced by a polymer-surfactant complex.⁸

Dynamic filtration of Formulation 1, with composition described in **Table 1**, was evaluated with a Fann 90 instrument, using aloxite cores ranging from 5 to 90 microns pore size. Samples of Formulation 1 were evaluated at a differential pressure of 500 psi, one without solid bridging agents and the other with 2.4% Rev-dust contamination. The results obtained with 5-micron, 20-micron and 90-micron cores are shown in **Figures 4, 5, 6, 7 and 8**. In all the tests, the internal filter cake is formed during the first 5 seconds, as we can see in the results obtained with 5, 20 and 90-micron cores. Once this internal filter cake is formed, the incremental filtration volume is minimal. These results also show no considerable increase in spurt loss when the permeability was increased from 2.8 Darcy (20-micron core) to 13.5 Darcy (90-micron core) (see **Figures 6 and 7**). The spurt loss also shows a considerable reduction when the fluid is formulated with 25 lb/bbl of calcium carbonate (**Figure 8**).

Formulation 1 contaminated with 2% Rev-dust was evaluated using a dynamic filtration device and PPA. The dynamic filtration evaluation, performed at a differential pressure of 500 psi using a 3-micron aloxite disk (0.45 Darcy), suggests good development of a primary filter cake during the one-minute spurt loss interval. The total filtration for the 30-minute test period was very low. The one-minute spurt loss measured in this evaluation was 3.7 mL and a cumulative filtrate volume of only 7.0 mL (**Figure 9**).

A PPA tester was used to conduct additional filtration testing. This static filtration test was performed in order to obtain data at high differential pressures. Testing at a pressure of 1500 psi on a 3-micron disk resulted in a spurt loss value of only 5.8 mL, while the cumulative volume was only 10.4 mL. This fluid, contaminated with

2% Rev Dust, reconfirms the beneficial value of small amounts of solids on the system's performance. Predictions suggest that higher differential pressures will result in higher spurt volumes, especially without bridging agents. To the contrary, the data indicate that increasing the differential pressure from 500 to 1500 psi only minimally affects long-term filtrate loss to the formation (See **Figure 10**).

A dynamic filtration test on a high permeability disk was performed with Formulation 1 containing only 25 lb/bbl of calcium carbonate. The results presented in **Figure 11** indicate a considerable reduction of filtrate volume in the presence of a small concentration of bridging agent, due to the excellent synergy of the surfactant-polymer complex with the calcium carbonate.

Temperature Stability

Thermal stabilizer additives can be added to the basic formulation in order to maintain the polymer stability in this system up to 149°C (300°F). **Table 2** gives the rheological properties of Formulation 1 after adding 8.6 kg/m³ (3 lb/bbl) of the inorganic stabilizer and 8.6 kg/m³ (3 lb/bbl) of Magnesium Oxide. The results indicate only minor variances between the rheological properties of the fluid at ambient temperature and those measured at 149°C (300°F).

Specialized Bridging Material

Although the original polymer-surfactant fluid design was solids-free, excluding bridging material, it was acknowledged early on that some reservoir conditions may require conventional bridging for improved filter cake development. In light of the system's inherent viscoelastic nature for inhibiting fluid invasion, it was discovered that some bridging selection models^{14, 15} currently used in the marketplace are not applicable to this fluid's design. The primary reason for this diversion results from two factors inherent within the final formulation. One factor, previously discussed, is the influence of the viscoelastic complex on spurt loss. The second factor is the inclusion of mixed particle shapes to form the filter cake.

Dynamic filtration, PPA and return permeability results with conventional calcium carbonate granules provided excellent bridging efficiency on low and medium permeability (300 -1800 mD) aloxite disks and Berea core samples. However, in highly porous media, such as 90 micron aloxite disk, excellent depositional results were observed with a low concentration blend of granules and flakes (See **Figure 12**). Both the granules and flakes are 95-99% acid soluble calcium carbonate.

It appears that the use of a low concentration of broadly distributed calcium carbonate granules blended with a small to medium PSD of flaked calcium carbonate particles significantly reduces spurt volumes relative to the use of only the granular form of calcium carbonate.

An extreme example, using flaked calcium carbonate

to improve bridging efficiency is shown in **Table 3**. In this PPA test, using a 90-micron aloxite disk, there was no attempt to select a proper PSD of the granular material so that the value derived from the flaked material could be demonstrated. In fact, the mean particle diameter of the graded calcium carbonate was less than one-seventh of the average pore diameter of the aloxite disk, a condition favoring deep invasion. The recorded low spurt and 30 minute filtrate volumes provide insight into the bridging efficiency credited to the flaked form of carbonate. In the case of Formulation 2, the spurt loss volume on the 90-micron disk was cut in half while the total filtrate volume was reduced by one-third with only 14.3 kg/m³ (5.0 lb/bbl) of additional flake material.

Compatibility of Design Fluid and Crude Oil

The possibility of water-in-oil emulsion formation in porous media is evaluated by using classical bottle tests. **Figure 13** shows the results of the tests performed with 50/50 and 25/75 heavy crude oil/drill-in fluid ratios at 77°C (170°F). For these specific tests, the crude oil/drill-in fluid proportions were blended at 300 rpm for 5 minutes and immediately placed into graduated cylinders, so that the rates of separation of the two phases could be measured. The results reveal that the samples attained complete separation in two hours, with a high separation in the first few minutes.

These results were expected because the polymer-surfactant blend has a moderate surface tension of about 35 dynes/cm. Surface tensions approaching zero are not desired because low surface tension promotes unwanted emulsions between crude oil and aqueous mud filtrates. Controlling interfacial behavior can greatly influence fluid flow in porous media by reducing the interfacial viscosity and elasticity.¹³ A fluid with a surface tension about halfway between the surface tension of water (74 dynes/cm²) and zero provides two advantages. A mid-value surface tension property promotes fluid mobility during production and avoids the formation of instantaneous emulsions, a condition that also reduces hydrocarbon mobility.

Results of compatibility tests conducted with crude oil and the drill-in fluid infer that emulsion blockage in reservoir pores is not probable.

Return Permeability

Return permeability testing was a critical part of the test matrix. These tests were conducted at 77°C (170°F) and with mud-off overbalance pressures of 1000 psi. The flow tests used mineral oil or PDVSA crude oil from a reservoir (VLA-1325) in Lake Maracaibo, Venezuela. The core samples used were Berea sandstone and field core from the VLA-1321 well.

The results obtained with the basic formulation contaminated with 2% Rev-dust included an 82% return

permeability in a Berea core and 85% from a field core taken at a depth of 5,902 ft (**Table 4**). Similar good results were obtained when 42.8 kg/m³ (15 lb/bbl) of granular calcium carbonate and 28.5 kg/m³ (10 lb/bbl) of flaked calcium carbonate were added to the system, which resulted in permeability values of 100%. Also important were the low break-through pressures required to initiate return flow. In all tests, the pressures required to initiate flow were less than 10 psi. Concurrent with the results obtained after 1500 psi PPA testing, the return permeability results with mud-off pressures up to 3000 psi suggest that formation damage variance with this fluid is minimal at high overbalance pressures.

Conclusions

1. Appropriate selection of a polymer-surfactant blend can result in a thermally-stable, low-density drill-in fluid system having high viscosity at low shear-rate (LSRV) and very small droplet size of internal phase synthetic (olefin).
2. The complexes formed by association of the polymer and surfactant provide appropriate rheological properties for excellent solids removal and hole cleaning.
3. Return permeability data and favorable fluid compatibility results suggest that this fluid is not damaging to producing formations.
4. The results of the dynamic and PPA tests at high overbalance pressures suggest that this fluid has good application for drilling low-pressure reservoirs without excessive fluid losses.
5. Granular shapes from conventionally ground calcium carbonate combined with a unique, flaked calcium carbonate material improve spurt loss and filter cake development in low and high-pressure environments.
6. Although not discussed in this paper, a North Sea "gold" rating has been assigned to the components used to formulate this system.

Acknowledgments

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References

1. Farmer, P., Miller, D., Pieprzak, R., J., and Woods, R.; "Exploring the Subsalt," *Oilfield Review* v. 8, No.1, (Spring 1996) 50 – 64.
2. Filippov, A, Mack, R., Cook, L., York, P., Ring, L., and McCoy, T.: "Expandable Tubular Solutions," SPE 56500, SPE Annual Technical Conference and Exhibition, Houston, Texas, Oct. 3-6, 1999.
3. Bennion, D.B.; Thomas, F.B.; Bietz, R.F.; and Bennion,

- D.W.: "Underbalanced Drilling: Praises and Perils," *SPE Drilling & Completion*, 13 (4), (December 1998) 214.
4. Kamp, A.; Celis, E.; Blanco, A.; Rivero, M.; Sharma, Y.; Atsushi, K.; and Tetsuo, Y.: "Aerated Drilling Proves its Worth in Venezuelan Reservoirs," *World Oil*, (March 2000) 51.
 5. Blanco, J.; Quintero, L.: "Oil in water emulsion well servicing fluids," U. S. Patent No. 5,783,525, July 1998.
 6. Quintero, L.; Bejarano, L.; Bellorin, L.: "Aplicación de la Tecnología INTEFLOW en Perforación de Pozos," XI Congreso Latinoamericano de Perforación, Buenos Aires, Argentina, Octubre 1998.
 7. Brookey, Tom "Micro-Bubbles: New Aphron Drill-In Fluid Technique Reduces Formation Damage in Horizontal Wells," SPE 39589, SPE International Symposium on Formation Damage Control, Lafayette, 1998.
 8. Miguel, M.G.; Marques, E.; Dias R.; Melnikov, S.M.; Khan, A.; and Lindman B.: "Associating Polymer-Surfactant Systems," *Progress Colloid Polymers Science*, 112, (1999) 157.
 9. de Gennes, P.G.: "Interactions Between Polymers and Surfactants," *The Journal of Physical Chemistry*, 94 (220) (1990) 8407.
 10. Piculell, L.; Thuresson, K.; and Lindman, B.: "Mixed Solution of Surfactant and Hydrophobically Modified Polymer," *Polymers for Advanced Technologies*, 112, (2001) 44.
 11. Lay-Theng Lee "Polymer-Surfactant Interactions: Neutron Scattering and Reflectivity," *Current Opinion in Colloid & Interface Science*, 4 (3), (1999) 205.
 12. Hallman, J. H.: "Formiatos en Accion: Uso en el Campo y Recobro," III Seminario de Fluidos de Perforación y Terminación de Pozos, Venezuela, Octubre 1996.
 13. Israelachvili, J.: "The Science and Application of Emulsions - an Overview," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, (91) (1994) 1.
 14. Ivanov, I.B.: Thin Liquid Films: Fundamentals and Applications, *Surfactant Science Series*, 29, Marcel Dekker Inc., New York (1988) 790.
 15. Miller, C.A.; and Neogi, P.: Interfacial Phenomena: Equilibrium and Dynamic Effects, *Surfactant Science Series*, 17, Marcel Dekker Inc., New York (1985) 299.
 16. Abrams, "Mud Designed to Minimize Rock Impairment due to Particle Invasion," *Journal of Petroleum Technology* (May 1977) 586.
 17. Dick, M.A.; Heinz, T.J.; Svoboda, C.F.; and Aston, M.: "Optimizing the Selection of Bridging Particles for Reservoir Drilling Fluids," SPE 58793, Symposium on Formation Damage, Lafayette, Texas, Feb 23-24, 2000.

Additives	Formulation		
	1	2	3
Water, bbl	0.95	0.95	0.95
Olefin, bbl	0.05	0.05	0.05
Polymer, lb/bbl	6	6	7
Surfactant, lb/bbl	3.5	6	6
Polymer Stabilizer, lb/bbl	5	5	5
Post 200°F Hot Roll Properties			
Plastic Viscosity, cPs	14	14	17
Yield Point, lbf/100 ft ²	50	51	63
6 rpm reading	24	24	31
3 rpm reading	20	20	27
10-sec/10-min/30-min gel, lbf/100 ft ²	20/26/28	21/26/28	26/31/34
Average droplet size, microns	< 5	<5	<5

Table 1 Effects of polymer and surfactant concentrations on fluid properties

Additives	Concentration	Properties	Initial	After HR @ 149° (300°F)
Water, bbl	0.95	PV, cP	19	12
Base oil, bbl	0.05	YP, lb/100 sq ft ²	60	55
Polymer, lb/bbl	6	3-rpm reading	23	23
Surfactant, lb/bbl	3.5	6-rpm reading	27	26
Polymer Stabilizer, lb/bbl	5	10-sec gel, lb/100 sq ft	23	22
Thermal stabilizers, lb/bbl	6	10-min gel, lb/100 sq ft	28	28
CaCO ₃ , lb/bbl	25			

Table 2 Effect of temperature on rheological properties

Filtration test using 90-micron disk		
Properties	Flake CaCO ₃	
	10 lb/bbl	15 lb/bbl
Spurt Loss, cc/1-min	4	2
Filtrate, cc/ last 29-min	30	20
Cake Thickness, mm:	1	1

Table 3 PPA results of fluid design with 15 ppb granular CaCO₃ and flake CaCO₃

	Basic Formulation		Formulation with 25 ppb CaCO ₃
	Berea	VLA-1321	Berea
Permeability	Crude	Crude	LVT 200
Initial Permeability, mD	268	23.7	1826
Final Permeability, mD	219	20.2	1826
Return Permeability, %	82	85	100

Table 4 Return Permeability Results

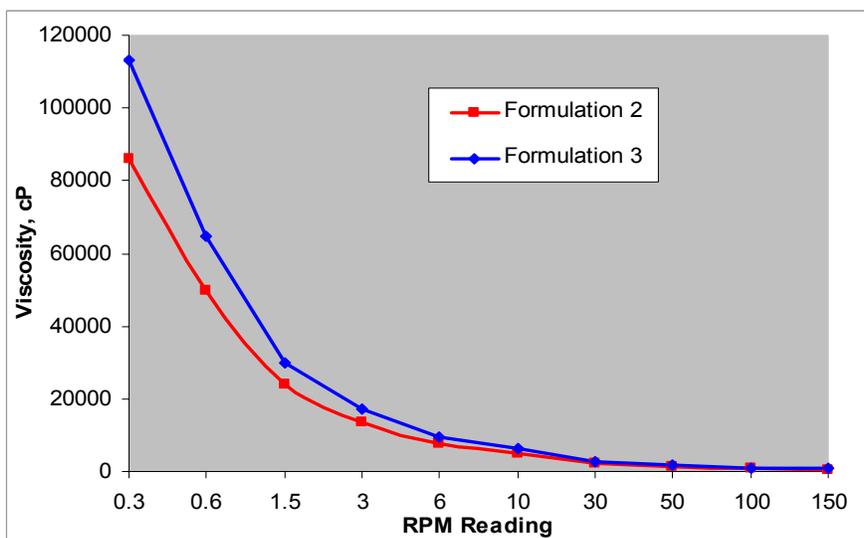


Figure 1 Low shear-rate viscosity measured with a Brookfield viscometer

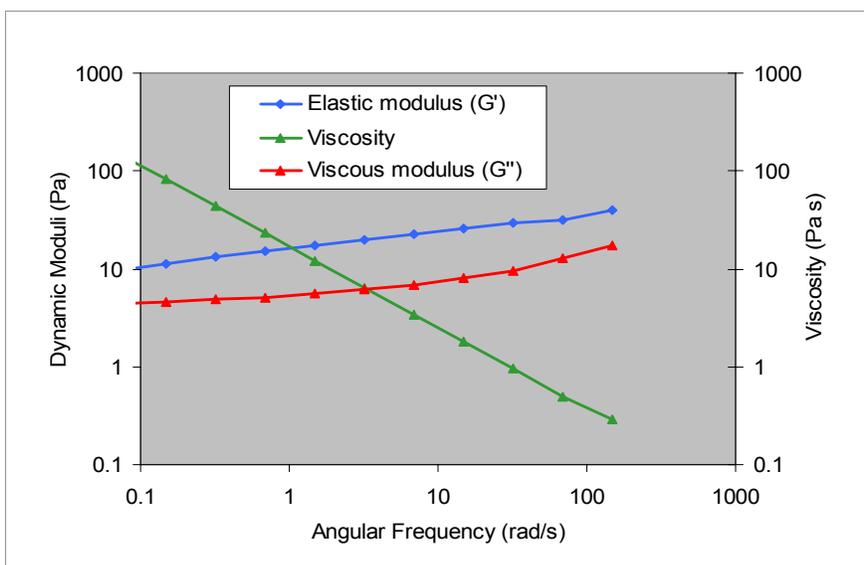


Figure 2 Viscoelastic properties of formulation 2

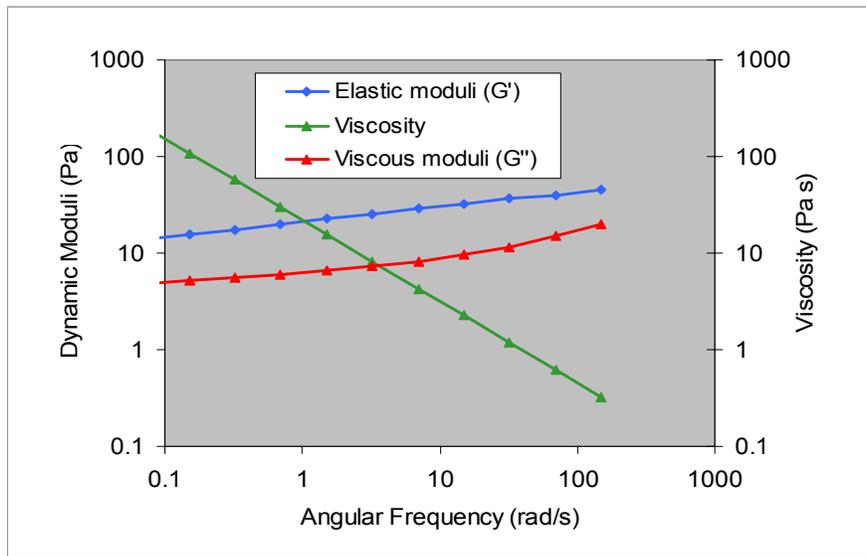


Figure 3 Viscoelastic properties of formulation 2 contaminated with solids

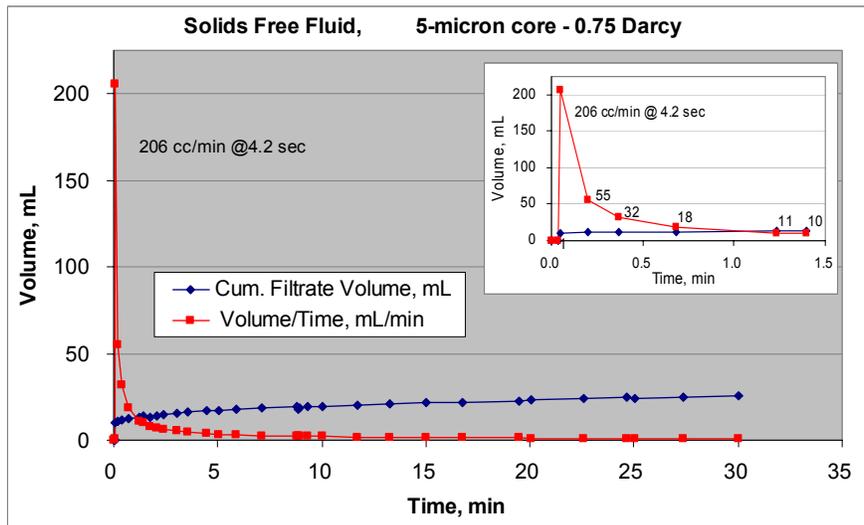


Figure 4 Dynamic filtration of solids free fluid with Fann 90 and 5-micron core

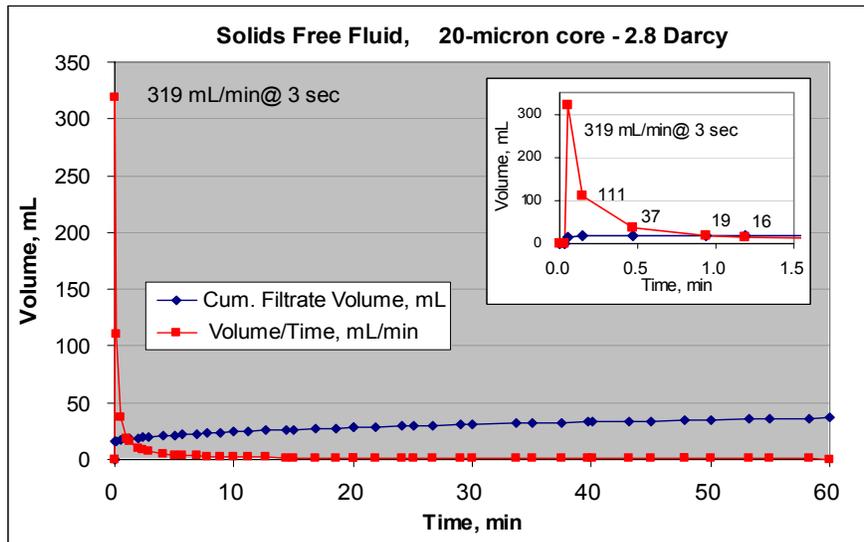


Figure 5 Dynamic filtration of solids free fluid with Fann 90 and 20-micron core

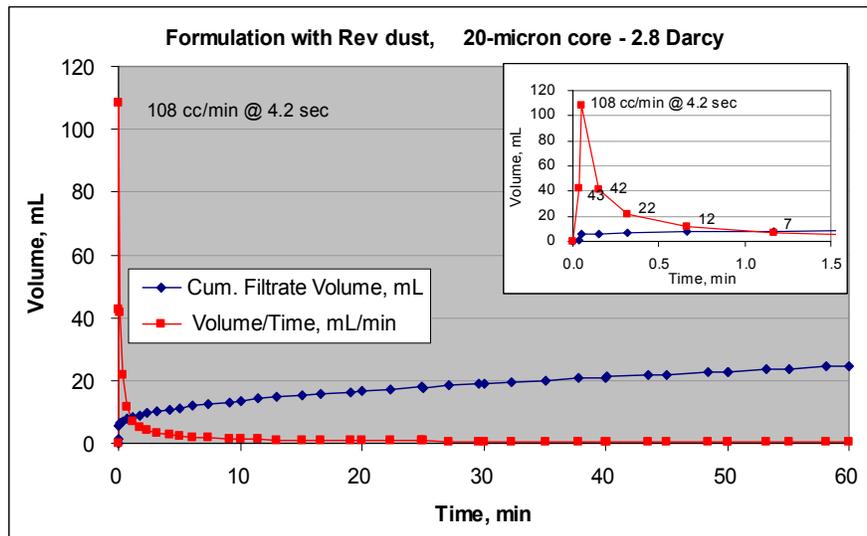


Figure 6 Dynamic filtration of fluid with Rev-dust using Fann 90 and 20-micron core

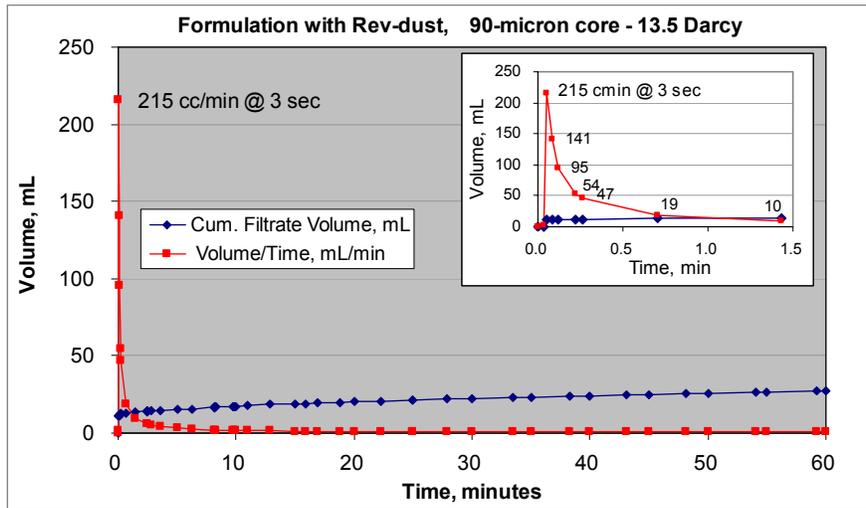


Figure 7 Dynamic filtration of fluid with Rev-dust using Fann 90 and 90-micron core

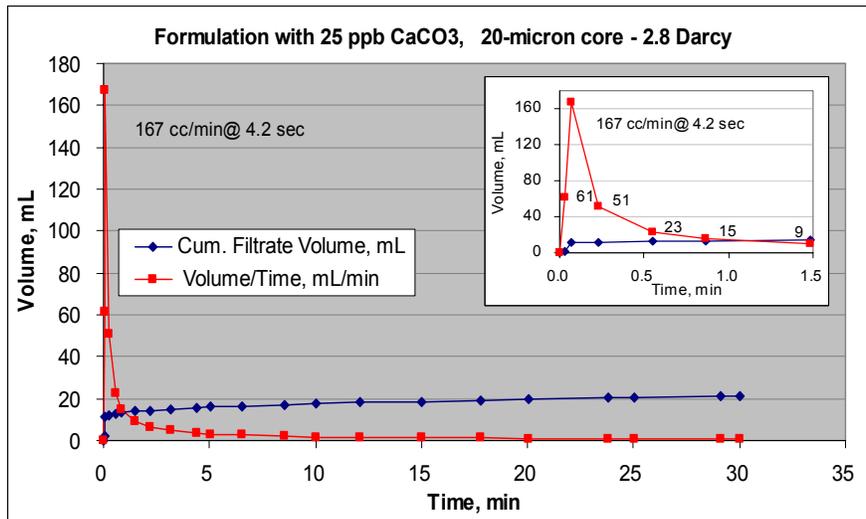


Figure 8 Dynamic filtration of fluid with CaCO₃ using Fann 90 and 20-micron core

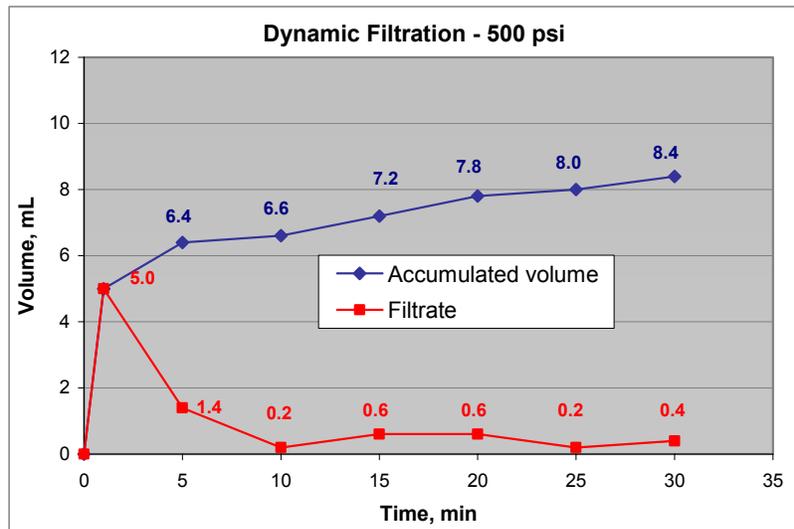


Figure 9 Dynamic filtration of formulation 1 with 2% Rev Dust

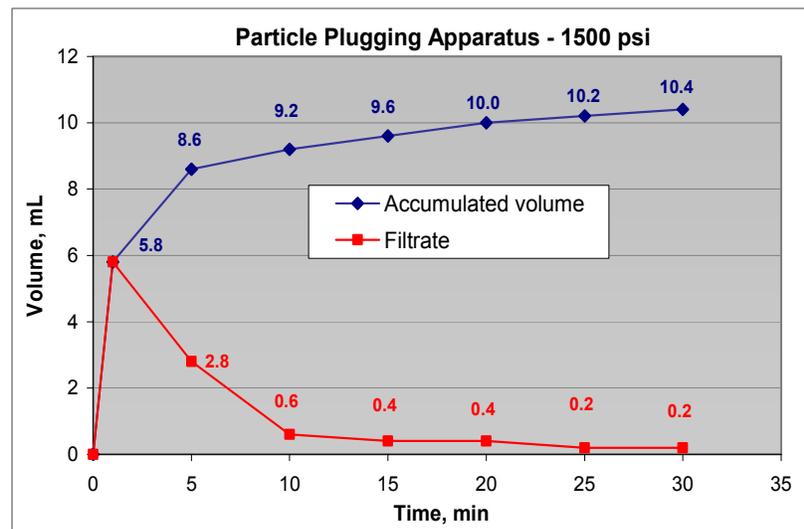


Figure 10 Static filtration (PPA) at 1500 psi

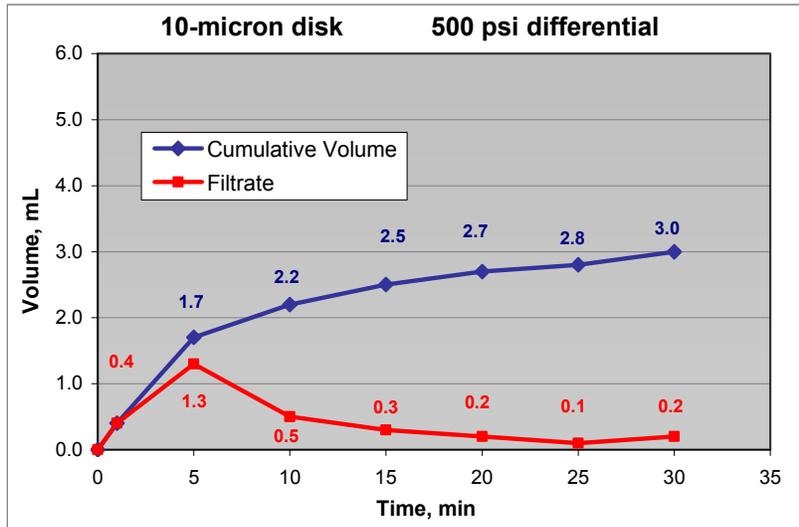


Figure 11 Dynamic filtration in a high permeability disk



Figure 12 Photograph of flake calcium carbonate

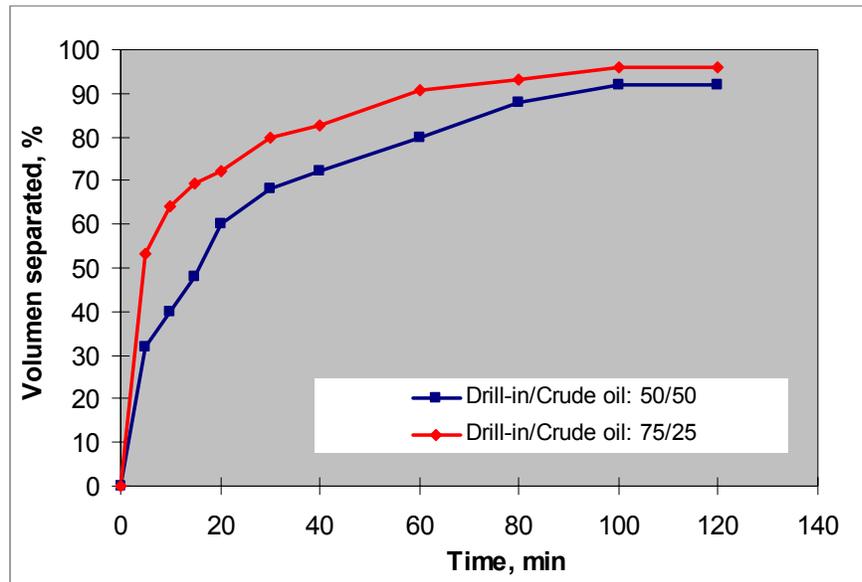


Figure 13 Drill-in fluid and crude oil compatibility