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How Aphron Drilling Fluids Work

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Proposal

Aphron drilling fluids, which are highly shear-thinning water-based fluids containing stabilized air-filled bubbles (aphrons), have been applied successfully worldwide to drill depleted reservoirs and other high-permeability formations. Although the performance of these fluids in the field is well documented, questions remain about how such fluids work. A study was initiated this past year under the auspices of the U.S. Department of Energy to develop some understanding of the mechanisms by which these fluids can seal loss zones with little permanent formation damage.

Among the key findings of this on-going project is that aphrons can survive elevated pressures for a much longer time than conventional bubbles, though they appear to be fairly sensitive to shear. In a loss zone, aphrons that survive the trip downhole can migrate faster than the base liquid and concentrate at the fluid front, thereby building an internal seal in the pore network of the rock. A microgel network formed by particulates in the drilling fluid aids the aphrons in slowing the rate of invasion, as does, of course, the radial flow pattern of the invasion. As the fluid slows, the very high LSRV (low-shear-rate viscosity) of the base fluid becomes increasingly important; this high LSRV, coupled with low thixotropy, enables the fluid to generate high viscosity rapidly. Bridging and formation of a low-permeability external filter cake also occur during the latter part of this period, ultimately reducing the rate of invasion to that of ordinary fluid loss.

Another key finding is that aphrons have very little attraction for each other or for mineral surfaces. Consequently, they do not readily coalesce nor do they stick easily to the pore walls, resulting in easy displacement by the produced fluids. In addition, the drilling fluid itself is very compatible with produced fluids and generates low capillary forces, thereby facilitating back-flow of produced fluids. The combination of these two effects is expected to result in low formation damage and minimal requirements for cleanup.

Introduction

Many oil and gas reservoirs are mature and are becoming increasingly depleted of hydrocarbons, which makes for evermore costly drilling. While the formations above and below these producing zones typically have much higher pore pressures and require high fluid density to stabilize them, exposure of a depleted zone to this high-density fluid can result in significant loss of whole drilling fluid and differential sticking.[1-4] Furthermore, pressured shales are often found interbedded with depleted sands, thus requiring simultaneous stabilization of multiple pressure sequences. Drilling such zones safely and economically is very difficult with conventional rig equipment.

Preventive measures with normal or high-density fluids generally entail use of a plugging agent at low concentration in the entire circulating system, or remediation if the rate of loss of drilling fluid exceeds some threshold level. While such techniques can be effective for controlling lost circulation in non-producing formations, the damage that these techniques can cause producing formations makes them wholly unsatisfactory for mitigating losses in oil and gas reservoirs.

An increasingly popular alternative for drilling depleted and multiple pressure zones is the use of underbalanced drilling, whereby the fluid has a density low enough to balance the pore pressure in the lowest-pressure zone. However, this technique requires additional equipment and risks wellbore collapse and blowouts. Aphron drilling fluids do not have such limitations. The air that is used to generate aphrons is usually incorporated into the fluid with conventional mud mixing equipment at ambient pressure, thereby reducing costs and safety concerns associated with air or foam drilling. Because the amount of air in the fluid is very low, the density of the fluid downhole is essentially that of the base fluid. Yet, the fluid is able to seal loss zones effectively and with minimal formation damage. Consequently, aphron drilling fluids are marketed as a cost-effective alternative to underbalanced drilling.

Although much is known about the performance of aphron drilling fluids in the field, questions remain about how such fluids work to minimize fluid invasion and formation damage. On-going laboratory work funded in part by the Office of Fossil Energy of the U. S. Department of Energy is serving to broaden understanding of the workings of aphron drilling fluids. In this paper we discuss the latest results of this study.

Aphron Drilling Fluids

The most dominant characteristics of aphron drilling fluids are their rheology and the presence of bubbles. The base fluid is highly shear-thinning and exhibits an extraordinarily high LSRV (Low-Shear-Rate Viscosity) with low thixotropy (flat gels). The bubbles of air that are dispersed in the base fluid are a dramatic departure from conventional fluids, because concerns over corrosion and well control have traditionally led to attempts to minimize air entrainment. Indeed, the air in aphron drilling fluids is purposely incorporated into the bulk fluid, but at a very low concentration. This occurs naturally during the course of product addition using conventional drilling fluid mixing equipment, and there is no need for high-pressure hoses and compressors such as those utilized in underbalanced air or foam drilling.[6]

The surfactants in the fluid convert the entrained air into highly stabilized bubbles, or "aphrons." However, in contrast to a conventional air bubble, which is stabilized by a surfactant monolayer, the outer shell of an aphron is thought to consist of a much more robust surfactant tri-layer.[5] This tri-layer is envisioned as consisting of an inner surfactant film enveloped by a viscous water layer; overlaying this is a bi-layer of surfactants that provides rigidity and low permeability to the structure while imparting some hydrophilic character.

It has been claimed that aphrons form a micro-environment in a pore network or fracture that behaves like a solid, yet flexible, bridging material. As is the case with any bridging material, concentration and size of the aphrons are critical to the drilling fluid's ability to seal thief zones. Although each application is customized to the individual operator's needs, the drilling fluid system is generally designed to contain 12-15 vol % air under ambient conditions, and the aphrons so generated are thought to be sized or polished at the drill bit to achieve a diameter of less than 200 µm, which is typical of many bridging materials.

Much of the scenario described above about the role of aphrons in reducing fluid losses downhole is conjecture that has not been confirmed under stringent laboratory conditions. Furthermore, the manner in which aphron drilling fluids reduce losses downhole is still not well understood.

Properties of Aphrons

In contrast to conventional bubbles, which do not survive long past a few hundred psi, aphrons have been found to survive compression to at least 4000 psig (27.7 MPa) for significant periods of time. When a fluid containing bubbles is subjected to a sudden increase in pressure above a few hundred psi, the bubbles initially shrink in accordance with Boyle's Law (Volume α Pressure^{-1}). Aphrons are no exception. However, conventional bubbles begin to lose air rapidly via diffusion through the bubble membrane, and the air dissolves in the surrounding aqueous medium. Aphrons also lose air, but they do so very slowly, shrinking at a rate that depends on fluid composition, bubble size, and rate of pressurization and depressurization.

Compression of a 500-µm diameter aphron from atmospheric pressure (0 psig) to 250 psig will reduce its diameter instantly to 191 µm, and compression to 2,500 psig will reduce it to 90 µm. At the same time, Henry's Law and the Lewis-Randall rule state that the solubility of a gas is roughly proportional to the pressure.[7] When a fluid containing 15 vol % entrained air at ambient pressure is compressed to just 250 psig, all of the air becomes soluble. If the stabilizing membrane surrounding a bubble is permeable, the air will diffuse out of the bubble and go into solution. This is what happens with ordinary bubbles, and it occurs within a matter of seconds after compression. Aphrons possess a much less permeable membrane, so they do not lose their air so readily. Indeed, when subjected to a pressure of 250 psig, aphrons will quickly shrink to the size predicted by Boyle's Law but will retain their air for hours.

Over short periods of time, aphrons can survive repeated compression and decompression. As shown in **Fig. 1**, rapid compression of an aphron drilling fluid from 0 psig to 3000 psig followed by decompression back to 0 psig results in essentially full regeneration of the aphrons.

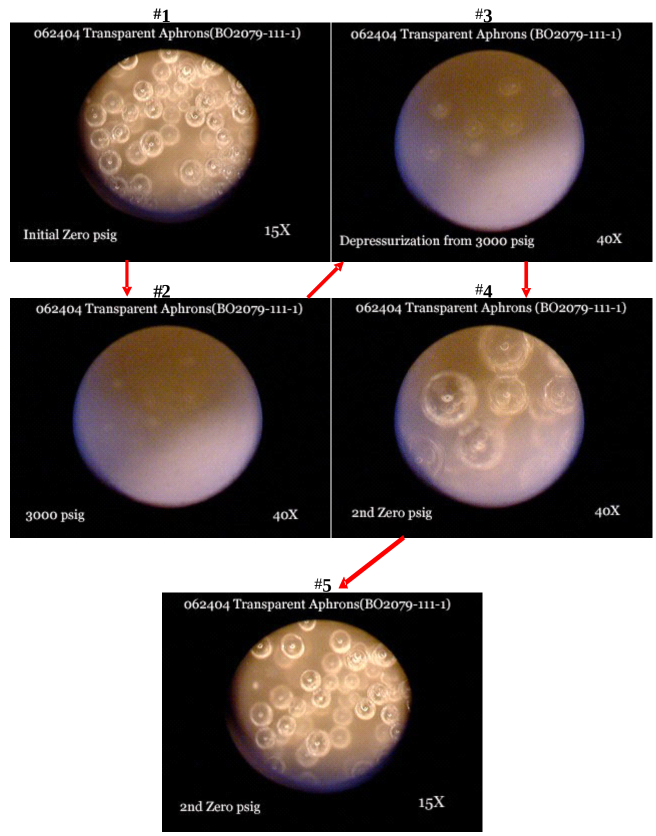


Fig. 1 – Rapid Pressure Cycling of Aphron Drilling Fluids Leaves Most Aphrons Intact (Note that photos #2 - #4 are at higher magnification)

Large aphrons (> 100 µm diameter) appear to be able to survive much better than small aphrons. **Fig. 2** shows the effect of the size of an aphron on its survivability. Aphrons of different sizes are pressurized from 500 psig to 2000 psig in steps of 500 psi. Large aphrons decrease in size with increasing pressure as expected from Boyle's Law; the small deviation is due to loss of air via slow diffusion into the surrounding fluid. When aphrons reach a critical size (50 to 100 µm diameter), they undergo a structural change that leads to their rapid demise, with the expelled air again dissolving in the surrounding fluid. The minimum diameter of the aphrons appears to be in the range of 25 to 50 µm, which agrees well with the minimum size of 25 µm estimated by Sebba for "colloidal gas aphrons."[5] If the fluid is decompressed to a pressure so low that the aqueous medium becomes supersaturated with air, i.e. it exceeds the solubility limit, the excess air is released; most of the air goes into existing aphrons, though new aphrons may also be created.

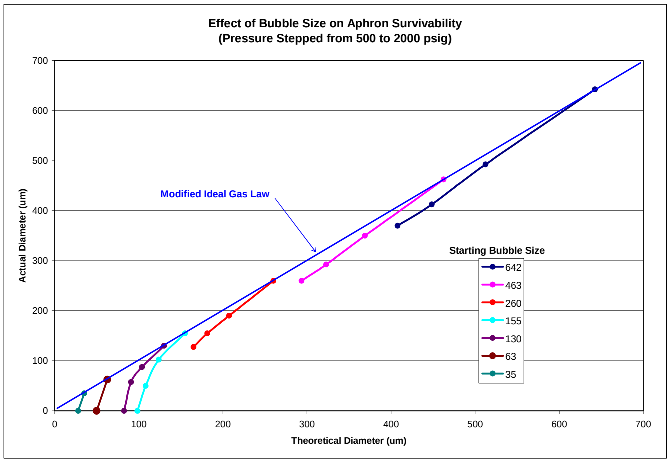


Fig. 2 – Aphron Longevity at Elevated Pressures Depends on Size

Aphron drilling fluids were improved recently through the addition of an aphron stabilizer package that yields more durable aphrons. The formulation of this "enhanced" system is shown in **Table 1**.

Table 1. Composition of Aphron Drilling Fluids

		Quantity per 350 mL	
Component	**Unit**	**Standard**	**Enhanced**
Water	mL	338	337
Soda Ash	g	3	3
X-CIDE	mL	0.1	0.1
GO-DEVIL II	g	5	5
ACTIVATOR I	g	5	5
ACTIVATOR II	g	2	2
BLUE STREAK	mL	0.91	0.91
APHRONIZER A	mL		0.5
APHRONIZER B	g		0.5
PLASTISIZER	mL		0.3

Fig. 3 shows that, for aphrons of similar size, the enhanced formulation yields aphrons that survive longer than those created with the standard formulation. These tests were carried out at 500 psig and room temperature under static conditions. Under dynamic conditions, shear forces may reduce stability further.

Another important finding is that the oxygen from the air in the aphron cores – indeed even the oxygen dissolved in the base fluid – is lost via chemical reaction with various components in the fluid, a process that usually takes minutes and results in the aphrons being filled primarily with residual nitrogen. Thus, corrosion of tubulars and other hardware by aphrons is negligible. **Fig. 4** shows that even at ambient temperature and pressure, the oxygen in solution in an aphron drilling fluid disappears within hours after preparing the fluid. By contrast, in a typical clay-based or polymer-based fluid, the concentration of oxygen in solution remains relatively constant.

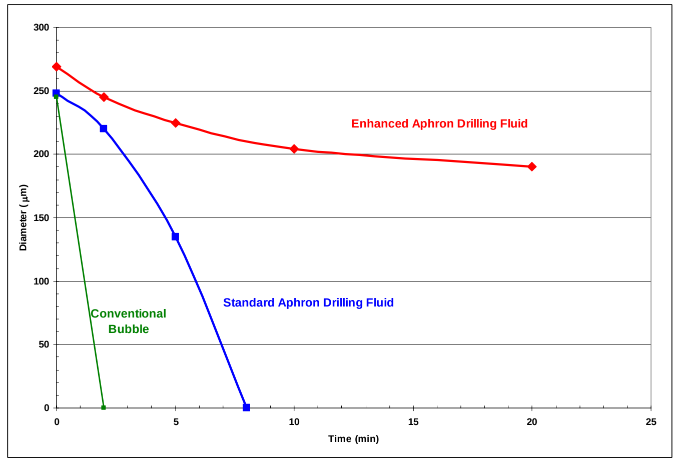


Fig. 3 – Longevity of Aphrons at Elevated Pressures is Much Greater than that of Conventional Bubbles 500 psig and Ambient Temperature

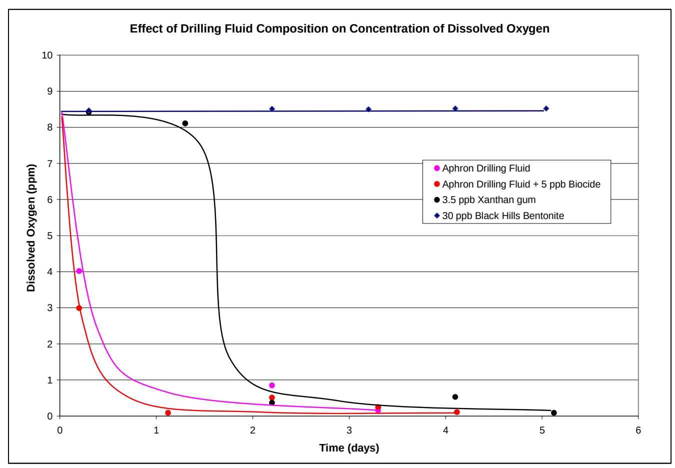


Fig. 4 - Oxygen in Aphron Drilling Fluids is Depleted Rapidly

Fluid Dynamics

The base fluid in aphron drilling fluids yields a significantly larger pressure loss (or lower flow rate for a fixed pressure drop) in long conduits than any conventional high-viscosity drilling fluid. The same results are observed when air is removed from the fluids, which in the lab is done using centrifugation. Similarly, if flow is restricted or stopped, aphron drilling fluids generate significantly lower downstream pressures than other drilling fluids. In permeable sands, the same phenomena are evident. However, at low to moderate pressures, aphrons themselves slow the rate of fluid invasion and increase the pressure drop across the sands. The lack of an aphron effect in open conduits appears to be related to their lack of effect on the viscosity profile of the fluid. As shown in **Fig. 5**, very little effect of air on shear stress (Fann Reading) is evident over the shear rate range 0.017 to 1000 sec^{-1} (Fann Speed = 0.01 to 600 rpm) at air concentrations up to at least 23 vol %. Above that concentration, high-shear-rate viscosity increases with increasing air concentration, but no effect is evident at very low shear rates.

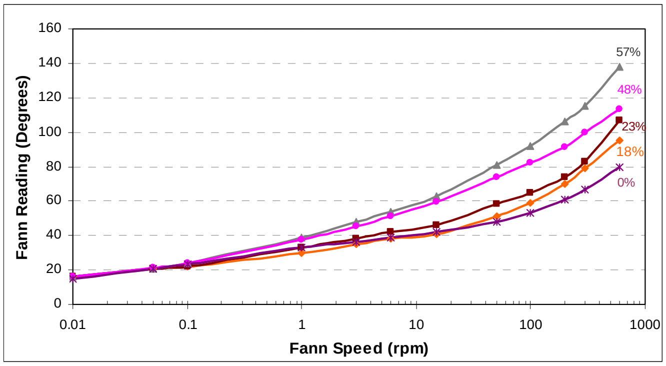


Fig. 5 –Viscosity Profile of Aphron Drilling Fluids is not Greatly Affected by Presence of Small Amounts of Air

In permeable sands, aphrons apparently interact with the pore walls and create a barrier to pressure transmission, thus increasing the pressure drop across the sand bed.

A key finding of this study was the phenomenon of "bubbly flow," which can leads to rapid transport of dispersed bubbles through the base fluid when the fluid is under the influence of a pressure gradient. **Fig. 6** demonstrates this bubbly flow phenomenon. A bed of 20/40 sand is initially saturated with water, which is displaced by an aphron drilling fluid during the test. Flow is from right to left under a pressure gradient of 100 psi. For ease of viewing, the mud sample used is a transparent aphron drilling fluid that has been dyed blue.

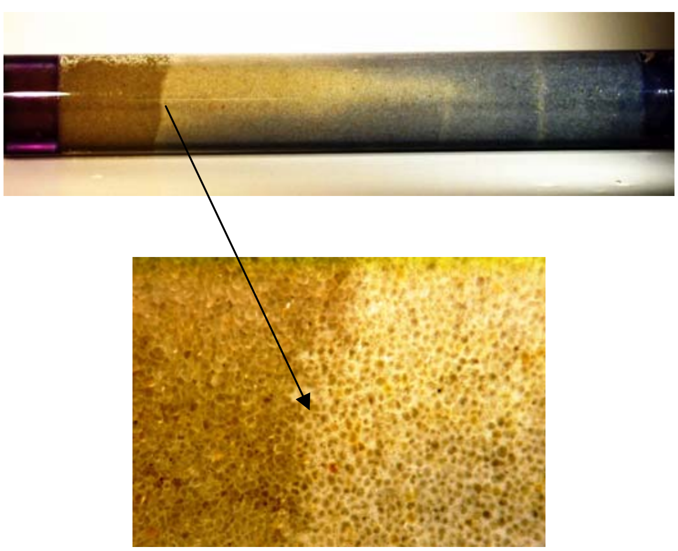


Fig. 6 - Aphron Drilling Fluid Displays Bubbly Flow during Displacement of Water in 20/40 Sand

The drilling fluid front is populated with a high concentration of bubbles that turns the fluid nearly white. High-density particles such as barite (a densifying material) or drilled cuttings tend to be left behind the base fluid. <u>Low-density internal phases, such as bubbles (aphrons), flow more rapidly than the base fluid</u>. Bubbly flow appears to follow conventional Navier-Stokes theory.[8] For a rigid sphere in a fluid under the influence of a one-dimensional pressure gradient, ΔP/L, the relative velocity of the bubble in an infinitely wide conduit is

$$V = 0.23\, r^2/\eta * \Delta P/L$$

where r is the bubble radius and η is the fluid viscosity. For flow through permeable media, the expression is modified to incorporate Darcy flow. Modeling of the flow of aphron drilling fluids in permeable media is currently underway.

Drilling Fluid Invasion

Static linear leak-off tests demonstrate that aphron drilling fluids are capable of sealing rock as permeable as 80 Darcy. **Fig. 7** shows some data for aphron drilling fluids in synthetic Aloxite cores with permeabilities of 0.75 to 10 Darcy. For each curve there is a high-rate spurt loss phase (whole mud invasion) during which the volume rises linearly with time and is roughly proportional to permeability. Aphron drilling fluids contain low levels of particulates that combine to form an external filter cake and shut down whole mud loss. Indeed, after the filter cake is established, the filtration rate is very low, though the cake is gelatinous and easily erodible. As indicated in **Fig. 7**, aphrons in the drilling fluid can reduce spurt loss below the level afforded by the base fluid. Detailed studies of the nature of this effect indicate that, at low pressures, aphrons can form what is tantamount to an internal seal, though they will also become an integral part of the filter cake. While they do not appear to affect the filter cake and filtration rate during establishment of the cake, during production at low pressures they may be released, leaving the cake pockmarked and easily penetrated during backflow of produced fluid.

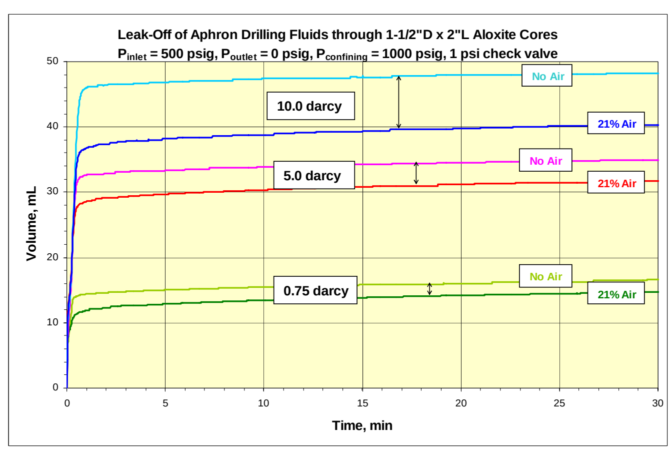


Fig. 7 - Aphron Drilling Fluids can Seal High-Permeability Formations

The role of aphrons in slowing whole mud invasion was investigated further, using the device drawn in **Fig. 8**. This apparatus utilizes two Variable Reservoir Depth (VRD) Viewing cells (#5) through while fluid is moved back and forth. Between these cells is a stainless steel filter that serves to simulate flow of the fluid into a permeable formation.

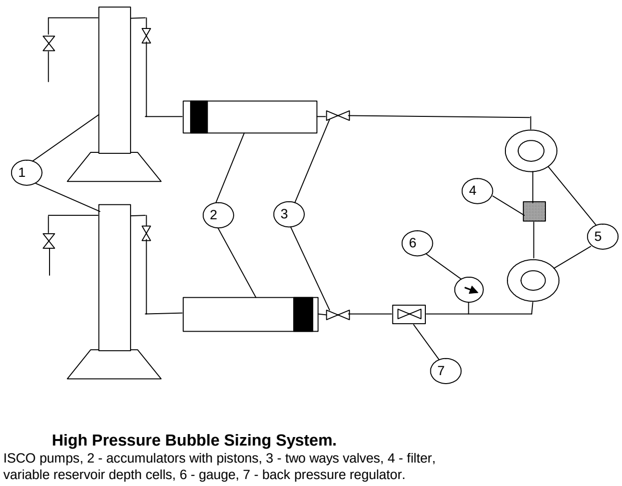


Fig. 8 - High-Pressure Aphron Filtration System

In tests conducted with a transparent aphron drilling fluid at close to ambient pressure using a filter with 15-μm openings, aphrons were easily comminuted; indeed, with increasing number of passes, the bubble size distribution became increasingly finer and narrower, as shown in **Fig. 9**.

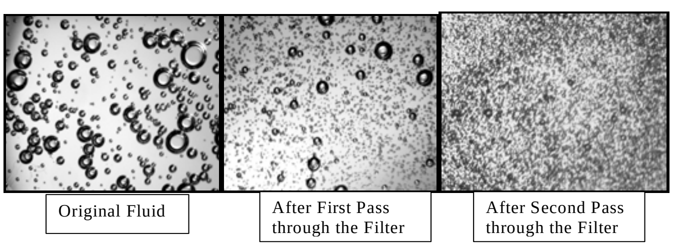


Fig. 9 – Bubble Size Distribution in Transparent Aphron Drilling Fluid Changes after Passage through 15-μm Filter

However, neither reducing bubble size (for a fixed amount of air) nor removing air from the sample affected bulk viscosity. This is demonstrated in the nearly identical Pressure vs Flow Rate data shown in **Table 2** that were gathered in a large-bore precision capillary tube. These data correspond to viscosity profiles that are more typically measured using concentric cylinder viscosimeters.

On the other hand, with increasing number of passes through the 15-μm filter, resistance to flow through that same filter did increase (see **Fig. 10**), strongly suggesting that the mechanism by which aphrons reduce mud invasion involves physical plugging, as with conventional lost circulation materials. The difference is that conventional materials generally are not deformable enough to automatically size themselves to fit pore throats.

Table 2 – Viscosity (Pressure vs Flow Rate in 500-μm capillary tube) of Aphron Drilling Fluid Is Not Affected by Passage through 15-μm Filter: P_{outlet} = 0 psig

	Inlet Pressure (psig)		
Flow Rate (mL/min)	Without Air	With Air: After First Filter Pass	With Air: After Second Filter Pass
0.5	**46**	**50**	**51**
1.0	**59**	**59**	**58**
2.5	**79**	**79**	**77**
5.0	**105**	**105**	**104**
7.5	**128**	**128**	**128**
10.0	**148**	**146**	**146**
20.0	**216**	**215**	**215**
25.0	**248**	**247**	**247**

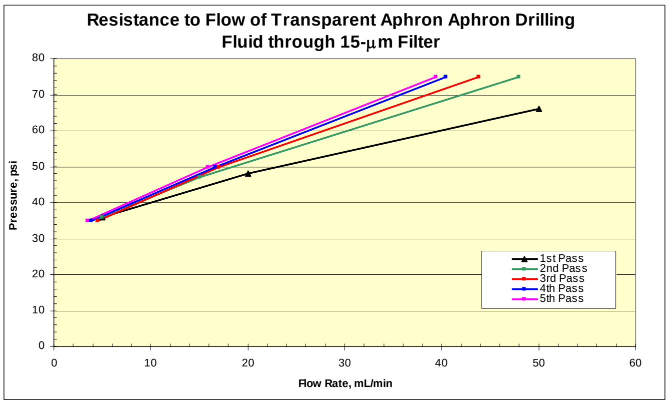


Fig. 10 –Resistance to Flow in 15-μm Filter of Transparent Aphron Drilling Fluid Increases after Multiple Passes through the Same Filter

However, at elevated pressure, another process plays a key role. As shown in **Fig. 11**, conducting the same filtration experiment as above under pressure leads to formation of bubbles whose size is below the 50 – 100 μm limit dictated by aphron stability principles,[5] resulting in rapid loss and dissolution of air.

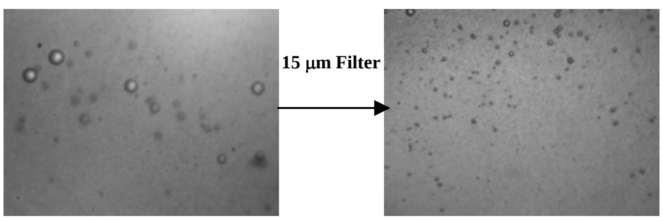


Fig. 11 – At 500 psig, Some Aphrons Disappear

Formation Damage and Cleanup

Return permeability tests carried out in Berea sandstone at 65.6 °C (150 °F), using inlet and outlet pressures of 2500 psig and 2000 psig, respectively, for the leak-off (damage) stage, indicate that the formation damage potential of this fluid is quite low and is similar to that of a well-constructed reservoir drilling fluid (**Fig. 12**).

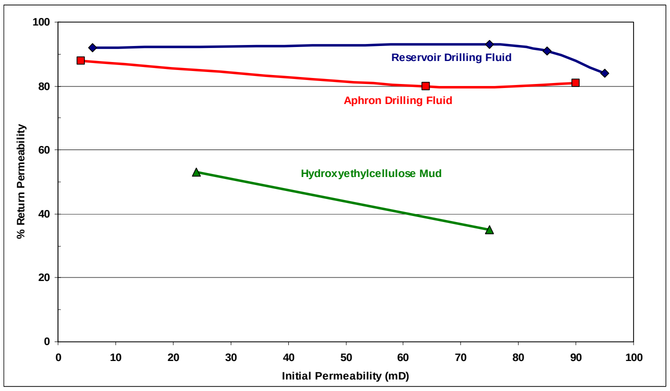
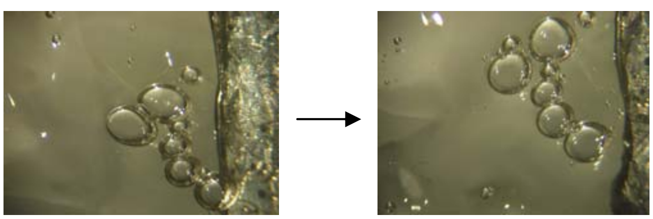


Fig. 12 - Return Permeability of Aphron Drilling Fluids is similar to that of Reservoir Drilling Fluids

Wettability tests indicate that aphrons have very little affinity for each other or for the mineral surfaces in rock formations encountered during drilling. This is demonstrated in **Fig. 13**, which shows bubbles that were purposely joined by creating them via air injection.



Created via Gas Injection **30 min Later**

Fig. 13 - Aphrons Exhibit Little Affinity for Each Other or for Mineral Surfaces

The bond between the bubbles is thought to be the result of imperfect development of the aphron shell. This does not occur during aphron generation under normal conditions. Even when created as a string of bubbles, within a few minutes the bubbles separate from each other, rather than coalesce. And, if the system is stirred, the bubbles separate immediately. Similarly, aphrons that have been purposed joined to a silica or limestone surface do not remain on the surface very long. This lack of affinity of bubbles for one another and for silica and limestone surfaces does not result from shedding surfactant layers, as was thought before, but is an intrinsic characteristic of the whole aphron structure. Thus, aphrons resist agglomeration and coalescence and are expected to be pushed back out of a permeable formation easily by reversing the pressure differential, thus minimizing formation damage and cleanup.

The base fluid in aphron drilling fluids is also very compatible with most other fluids commonly encountered in the field. Not only is the base fluid compatible with other water-based fluids, but also with hydrophobic fluids, such as produced oils. As shown in **Fig. 14**, a drop of a high-asphaltene highly viscous Canadian crude oil on a glass slide covered with an aphron drilling fluid gives a very low contact angle. Although the oil does not actually spread on the drilling fluid-treated surface (contact angle ~ 5 deg), incompatibility between the two fluids would result in a much higher contact angle and might even be expected to form a separate phase.

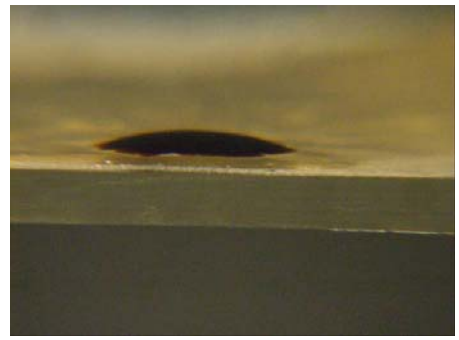
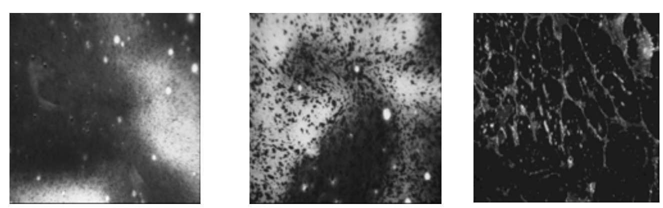


Fig. 14 – Crude Oil Nearly Spreads on Glass Surface Pre-Treated with Aphron Drilling Fluid

Additional evidence for the compatibility of aphron drilling fluids and oils can be obtained by mixing the two fluids and observing the nature of the continuous and discontinuous phases. As shown in **Fig. 15**, mixing up to at least 25 vol % of the same oil described above into the drilling fluid continued to yield a water-continuous (water-wet) system, with the oil dispersed as black specks and the aphrons visible as white disks.



Mud/Oil = 90/10 **75/25** **50/50**

Fig. 15 – Aphron Drilling Fluid Mixes Readily with Canadian Crude Oil and is Water-Continuous up to at Least 25 vol % Oil

At 50 vol % oil, the system became oil-continuous, with the aphron drilling fluid appearing as rivulets. Interestingly, during the transition from water-wet to oil-wet, the viscosity hump was almost negligible.

Finally, flow tests of oils through a bed of 2-mm glass beads saturated with aphron drilling fluid showed that the oils did not channel and move around the drilling fluid as might be expected for displacement of a high-viscosity fluid with a low-viscosity fluid. Instead, the oil coursed through the drilling fluid with relative ease and some even became incorporated in the drilling fluid before exiting the flow cell.

Conclusions

Aphron drilling fluids possess three chief attributes that serve to minimize fluid invasion into low-pressure permeable or fractured formation. First, aphrons that survive comminution experience bubbly flow; this phenomenon propels aphrons rapidly to the fluid front, where they concentrate and form a soft internal seal that reduces the rate of fluid invasion. Aphrons are capable of carrying out this task by virtue of their stability at elevated pressures; conventional bubbles cannot do this. Second, particulates form a microgel network with surface-active agents and polymers that slows progress of the fluid even more. Third, when the rate of of invasion is slowed sufficiently, the very high LSRV (low-shear-rate viscosity) of the base fluid slows the rate of fluid transport even more; the low thixotropy of the fluid enables it to respond quickly and generate high viscosity rapidly. By this time, bridging occurs and an external filter cake of very low permeability is established, which reduces the rate of loss of fluid to that of ordinary filtration.

Aphron drilling fluids also possess some attributes that may prove beneficial for production. Aphrons have little affinity for each other or for rock surfaces, thereby enabling them to be produced back with relative ease. Furthermore, the fluids themselves appear to be fairly compatible with hydrophobic phases

Acknowledgements

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SI Metric Conversion Factors

bbl	X 0.159	= m^3
cP	X 1.00	= mPa-s
°F	(°F-32) X 5/9	= °C
ft	X 0.3048	= m
gal	X 0.00379	= m^3
in	X 0.0254	= m
lb	X 0.454	= kg
lb/bbl	X 2.853	= kg/m^3
lb/gal	X 119.8	= kg/m^3
lb/gal	X 0.120	= Specific Gravity (sg)
lbf/100 ft^2	X 0.478	= Pa
psia	X 6.895	= kPa
psig	+ 14.7	= psia