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Recent Advances in Aphron Drilling Fluids

F. B. Growcock, A. Belkin, M. Fosdick, M. Irving, B. O'Connor and T. Brookey, MASI Technologies and M-I SWACO

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Abstract

Aphron drilling fluids are being used globally to drill through depleted reservoirs and other under-pressured zones. The primary features of these fluids are their unique low-shear rheology and aphrons (specially designed pressure-resistant microbubbles of air). However, how aphron drilling fluids work is not well understood, which limits acceptance of this technology, along with efforts to optimize the system's performance. Recently a study was undertaken under the auspices of the U.S. Department of Energy to gain some understanding of the workings of aphron drilling fluids. Those results are presented here.

Various laboratory techniques were applied to determine the physicochemical properties of aphrons and other components in the fluid and how they affect flow through permeable and fractured media. These included wettability and surface tension, bubble stability, radial and dynamic flow visualization, and fluid displacement tests.

One key discovery was that aphrons can survive compression to at least 4000 psig, whereas conventional bubbles do not survive long past a few hundred psig. When drilling fluid migrates into a loss zone under the drill bit, aphrons move faster than the surrounding liquid phase and quickly form a layer of bubbles at the fluid front. At the same time, the shear rate of the fluid continually decreases and the viscosity is rapidly rising. The combination of the bubble layer and the rapidly increasing viscosity of the liquid severely curtails fluid invasion. Another key finding of the study is that aphrons show little affinity for each other or for the mineral surfaces of the pore or fracture; consequently, the seal they form is soft and their lack of adhesion enables them to be flushed out easily during production.

Depleted wells which are very expensive to drill underbalanced or with other remediation techniques can now be drilled overbalanced. This study has provided a sound technical basis for the success of aphron drilling fluids and is providing guidance on the way to run these fluids in the field to optimize their performance.

Background

Aphrons were first described by Sebba[1] as unique microspheres with unusual properties. Much of his work was done with microbubbles consisting of air encapsulated in a multi-layer shell created and maintained via chemical equilibrium with various components in the base fluid. Brookey[2] described the first use of aphrons in a drilling fluid application. In this case, the microbubbles (as they were then called), were created as a minor phase in a water-based fluid. This system was used as a means of controlling lost circulation and minimizing formation damage in a low-pressure vugular dolomite reef zone. The microbubbles allowed the zone to be drilled to required TD, logged and drill stem-tested; this had not been possible previously. How did the fluid system work? Many at that time thought that density reduction was responsible, since the application resulted in a lower mud weight on surface.

The next application was in a fractured dolomite horizontal well, where the bit dropped only a foot and all returns were being lost. In this application, full returns were resumed as soon as the microbubbles reached the bit. Obviously density reduction was not the reason these losses were controlled. This experience led to further research in the area of foams and aerated fluids and to the discovery of Sebba's work with aphrons.

Reformulation of the drilling fluid led to increased stability of the aphrons through re-engineering of the multi-layer shell and enhancement of the low-shear-rate viscosity (LSRV), which made the fluid more effective in downhole applications.

This new system was applied in South America in an area where six wells were drilled using various fluids and techniques, including underbalanced drilling. Because of severe depletion, lost circulation and borehole instability, none of these wells was successfully drilled to TD. Ramirez[3] described the application of aphron technology in this field, which resulted in no drilling fluid losses and excellent wellbore stability even in previously troublesome shale sections. Conditions were so favorable that coring was done with over 90% recovery on the first well. Extensive wire-line logging was carried out with no problems. Even cementing was highly successful, with full returns throughout, though severe cementing problems had been the norm. After drilling the first three wells in this field, the operator was able to eliminate the intermediate string and drill from surface casing to TD successfully.

Fig. 1 shows the results of an RFT log in this field and demonstrates the effect of compression on aphrons and the actual hydrostatic pressure downhole.

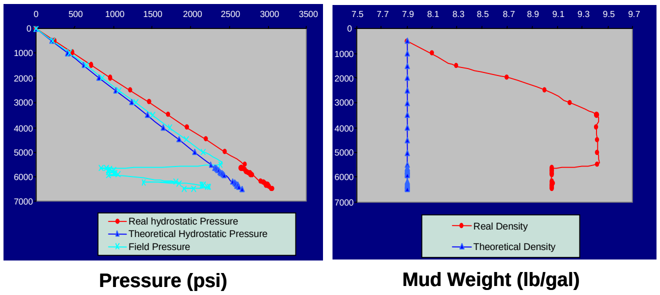


Fig. 1 – RFT Log of Aphron Drilling Fluid used to drill in South American field

The red line indicates the true hydrostatic pressure, while the dark blue line shows the theoretical hydrostatic pressure derived from surface measurements. The difference is the approximate aphron (air) concentration in the fluid. The light blue line shows actual formation pressure. This demonstrates a tremendous overbalance across the highly permeable sand; no losses were experienced, yet the hydrostatic pressure was sufficient to stabilize the impermeable shale section. This ability to drill under-pressured zones may permit elimination of the intermediate casing string on future wells.

Kinchen[4] describes drilling in a highly vugular, fractured dolomite zone with good success, even coring with this fluid. Besides lost circulation control, these wells came on with full production in 4 days versus 30 to 60 days average in previous wells drilled with various fluid programs.

Gregoire[5] chronicles a program of drilling with an aphron drilling fluid and controlling losses in a fractured granite zone, which resulted in open-hole production almost instantaneously without treatment. Besides instant cleanup, the production rates were much higher than had been seen before with any other drilling fluid.

Although aphron technology has been successfully used in about 300 wells over a period of several years, it was desirable to develop a deeper understanding of the way aphron drilling fluids work and to utilize laboratory techniques for optimizing field applications. The initial and predominant type of aphron drilling fluid used in the field has been a polymeric water-based system, though a clay water-based alternative and a nonaqueous-based aphron drilling fluid have also been developed.[6,7] A two-year research and development program was undertaken under the auspices of the U.S. Dept. of Energy to obtain laboratory evidence for the capability of aphron drilling fluids – primarily the polymer water-based system -- to limit fluid invasion in permeable formations with minimal formation damage, and to provide a sound scientific basis for this behavior.[8] The following describes some of the results of this study.

Aphron Formation and Longevity

A representation of an aphron is shown in **Fig. 2**. This schematic illustrates Sebba's concept of a gas core (air, in the case of aphron drilling fluids) that is enveloped by a surfactant tri-layer, within which is a semi-solid aqueous layer. The outer surfactant layer is thought to be polar (hydrophilic), making the aphron structure compatible with the surrounding water-based fluid.

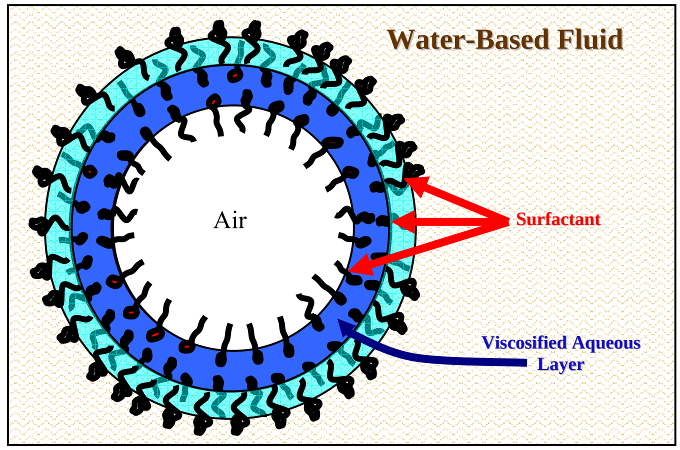


Fig. 2 – Schematic of an aphron (after Sebba[2])

Effective aphrons possess a strong, impermeable shell. This helps to prevent leakage of air from the core and allows the aphrons to survive downhole pressures. It also determines how long the internal seal in a permeable formation can be made to stay in place. Recently the polymer-based aphron drilling fluid was modified to provide even greater stability for the aphrons. This was accomplished, as shown in Table 1, via the addition of a blend of polymer and surfactants called "Aphron Stabilizer."

Table 1 – Composition of Polymer-Based Aphron Drilling Fluids

		Quantity per 350 mL	
Component	**Unit**	**Standard**	**Enhanced**
Water	mL	338	337
Soda Ash	g	3	3
Biocide	mL	0.1	0.1
Viscosifier	g	5	5
Thermal Extender	g	5	5
Alkalinity Control Agent	g	2	2
Aphron Generator	mL	0.91	0.91
Aphron Stabilizer	mL		1.3

As shown in **Fig. 3**, aphrons survive exposure to elevated pressures much better than conventional bubbles, and enhanced aphrons have greater longevity than standard aphrons. Here a conventional bubble and bubbles from standard and enhanced aphron drilling fluids were selected which measured about 250 μm diameter when first prepared at atmospheric pressure. When compressed to 500 psig and maintained at that pressure, all three bubbles immediately shrank to about 150 μm. Within 2 min, the conventional bubble had disappeared, whereas the enhanced aphron disappeared in less than 10 min and the enhanced aphron survived more than 30 min.

Aphrons are formed spontaneously when air is incorporated into the fluid during the course of product addition. Conventional drilling fluid mixing equipment is used for these additions, and there is no need for high-pressure hoses and compressors, such as those utilized in underbalanced air or foam drilling. Aphrons constitute a major phase of the drilling fluid at atmospheric pressure (usually 10-15 vol %). Within minutes of preparing an aphron drilling fluid, the oxygen fraction of the entrained air is lost via reaction with a cellulosic component of the mud.[9] This leaves the aphrons filled primarily with nitrogen. This eliminates concerns about corrosion downhole. Although elimination of the oxygen also results in some shrinkage of the aphrons, the reduction in aphron diameter -- about 7% -- is not expected to affect the performance of the aphrons significantly.

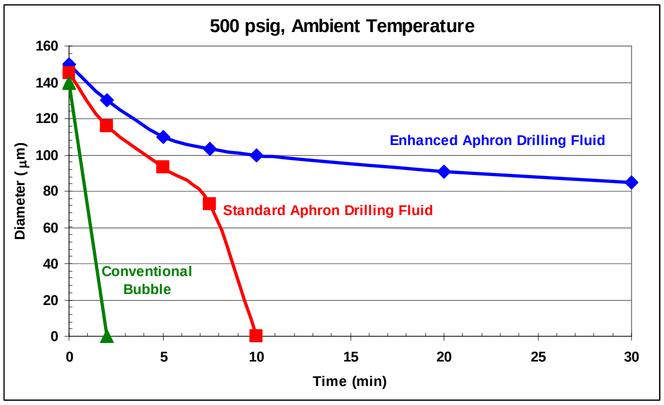


Fig. 3 – Aphrons withstand elevated pressures much better than do conventional bubbles

At downhole pressures, aphrons occupy an almost insignificant volume, e.g. a mud sample containing 12 vol % nitrogen at atmospheric pressure will contain less than 0.06 vol % nitrogen at 3000 psig. Thus, there is little effect of the aphrons on mud density. Compression of the aphrons downhole allows the fluid to maintain a stable and predictable hydrostatic and circulating pressure for wellbore control and stability. When the drilling fluid enters a formation, the aphrons expand and, as discussed later, will concentrate at the fluid front to create a "micro-environment" that separates the borehole from the formation pressures, effectively putting the borehole and formation "at-balance." This aphron phase is effective even though the fluid is recirculated and handled like a conventional circulating fluid.

When a fluid containing aphrons is subjected to a sudden increase in pressure above a few hundred psig, the aphrons initially shrink in the same manner as conventional bubbles, i.e. in accordance with Boyle's Law (Volume α Pressure^{-1}). However, conventional bubbles begin to lose nitrogen rapidly via diffusion through the bubble membrane, and the nitrogen dissolves in the surrounding aqueous medium. Aphrons also lose air, but they do so much more slowly, shrinking at a rate that depends on fluid composition, bubble size, and rate of pressurization and depressurization.

The solubility of gases in liquids is described by Henry's Law and the Lewis-Randall rule, which state that the solubility of a gas is roughly proportional to the pressure.[10] When a fluid containing 15 vol % entrained air at ambient pressure is compressed to just 250 psig, essentially 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 as readily. Indeed, when subjected to a pressure of 250 psig, aphrons will quickly shrink to the size predicted by Boyle's Law, but they will retain their nitrogen for hours.

The rate of diffusion of nitrogen from conventional bubbles under pressure is expected to be proportional to the bubble size (radius or diameter), which is given by the product of the driving force (the excess pressure between the bubble and the medium, which is inversely proportional to size) and the leakage rate (proportional to surface area).[11] However, for aphrons, the diffusion rate was found to be proportional to the surface area of the bubble, i.e. the rate of loss of nitrogen from aphrons decreases more rapidly with decreasing size than is the case for conventional bubbles.[9] For aphrons, the increase in driving force that normally accompanies a decrease in size of the bubble may be nullified by a decrease in permeability as the shell is compacted.

When aphrons become smaller than about 50 µm diameter, they become less stable and suffer catastrophic loss of air.[9] Clearly, the mechanism for nitrogen loss changes below this critical size and does not follow the diffusion behavior described above. This agrees with Sebba's hypothesis that aphrons smaller than 25 µm diameter may not be able to survive, due to the inability of the surfactant tri-layer in the aphron shell to assume a very high radius of curvature and pack properly around the gas core.[2]

Aphrons can survive compression to at least 4,000 psig in laboratory tests. **Fig. 4** shows the ability of aphrons to survive during compression and recover or regenerate during decompression. In this case, the maximum applied pressure was 3,000 psig.

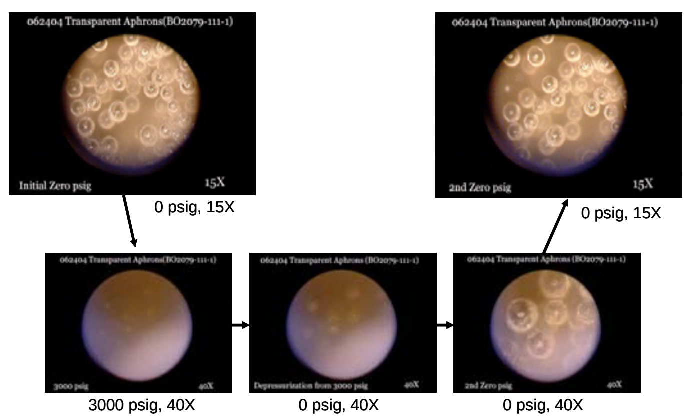


Fig. 4 – Rapid Pressure Cycling of Aphron Drilling Fluids Leaves Most Aphrons Intact

Aphrons are also affected by the rate of pressurization and/or depressurization. Rapid changes in pressure appear to affect the stability of aphrons much less than slow changes in pressure.[9] This may seem counter-intuitive, inasmuch as slow changes would permit the surfactants and polymers in the aphron shell to rearrange more completely when the pressure (aphron size) is changed. One explanation is that, during the initial stages of pressurization, the aphron shell compacts and contains an excess of surfactants and polymer, which is expected to decrease its permeability.

Aphrons are strongly affected by shear, as well as pressure. In previously reported tests,[9] aphrons were easily comminuted by passing the drilling fluid through various types of filter media. Indeed, with increasing number of passes through a filter, the bubble size distribution became increasingly finer and narrower. However, for air concentrations less than 15 vol %, neither reducing the bubble size nor removing air from the sample affected the bulk viscosity of the fluid. On the other hand, resistance to flow through that same filter did increase, suggesting that aphrons behave as conventional lost circulation materials, i.e. aphrons reduce fluid invasion by physically plugging pores or fractures.

Bubbly Flow

Popov[12] describes "bubbly flow", a phenomenon where the aphrons move at a much faster rate than the bulk fluid and form an aphron layer. Bubbly flow appears to follow conventional Navier-Stokes theory, so that the relative velocity of a rigid bubble in an infinitely wide conduit is

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

where r is the bubble radius, η is the fluid viscosity and ΔP/L is the pressure gradient. Thus, for maximum effect, aphrons should be large, viscosity low and pressure gradient high. For flow through permeable media, the expression is modified to incorporate Darcy flow, but it retains the basic form shown above. Thus, as demonstrated in **Fig. 5**, large aphrons move faster than smaller ones, as predicted by Navier-Stokes theory.

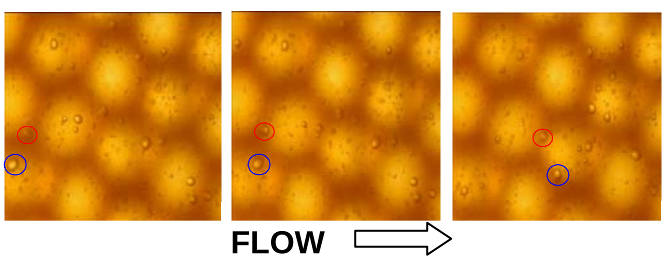


Fig. 5 – Velocity of aphrons increases with increasing size. The bubble in the blue circle is about 25% larger than the one in the red circle.

Aphrons can accumulate at the fluid front and inhibit movement of the liquid particularly during the initial stages of fluid invasion, when fluid viscosity is lowest and the pressure gradient is the highest. Although the amount of air in a typical aphron drilling fluid is very small (15 vol % air at ambient conditions constitutes only 0.02 wt % air), there is a sufficient number of aphrons that bubbly flow can play a role in limiting fluid invasion.

Popov calculates that in radial flow geometry, such as that experienced downhole when fluid penetrates a loss zone, fluid invasion can range from a fraction of a meter to several meters. Almost immediately after invasion begins, a band of bubbles of constant thickness is formed at the fluid front and slows progress of the fluid through the permeable medium. Simulated radial flow tests at low pressures confirm this, as shown in **Fig. 6**.

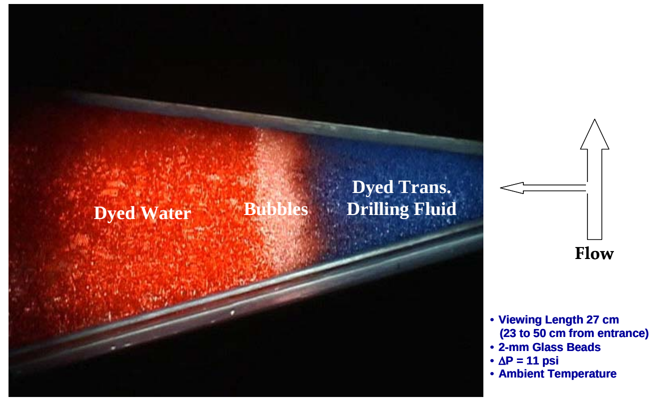


Fig. 6 - Bubbly flow of aphrons produces a band of bubbles of constant thickness at the interface between the drilling fluid and the reservoir fluid.

At elevated pressures (where the fluid is not saturated with nitrogen), comminution of aphrons via shear occurs in the pore or fracture network, and this will result in some loss of aphrons. However, if sufficient aphrons survive this trip, the fluid in the aphron band becomes saturated with nitrogen. Aphrons which arrive thereafter will accumulate. Furthermore, although comminution of the bubbles will result in some loss of aphrons, it will also reduce the surviving aphrons to a size similar to that of the pore/fracture openings. As such, they are of ideal size to serve as bridging materials, and they will reduce the rate of movement of the fluid.

Compatibility with Formations and Produced Fluids

Notwithstanding their polar nature, aphrons exhibit little affinity for each other or for rock surfaces. As shown in **Fig. 7**, when aphrons are created as a string of bubbles attached to a silica surface, in time they separate and detach themselves from the surface.

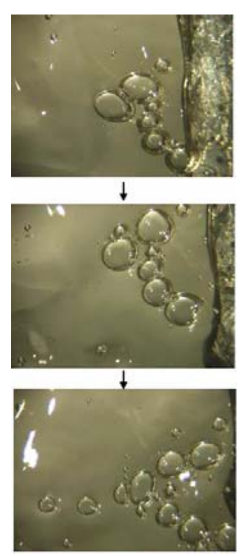


Fig. 7 - Aphrons do not stick to each other or to the walls of pores and fractures.

Thus, aphrons resist coalescence and aggregation, and they remain as discrete bubbles in the circulating fluid or when decompressed during fluid invasion. This low wettability is expected to lead to easy cleanup of the pay zone during completion.

The base fluid itself plays a large role in the interaction of aphron drilling fluids with produced fluids. Large amounts of crude oils – generally as much as 25 to 50 vol % -- can be blended with aphron drilling fluids and still be water-wetting. An example of this is shown in **Fig. 8**, which is a 50/50 mix of a crude oil and an aphron drilling fluid.

Fig. 8 – Dispersion of 50 vol % each of a crude oil and an aphron drilling fluid.

Microscopic examination reveals that this system contains dispersed oil, along with aphrons (see **Fig. 9**).

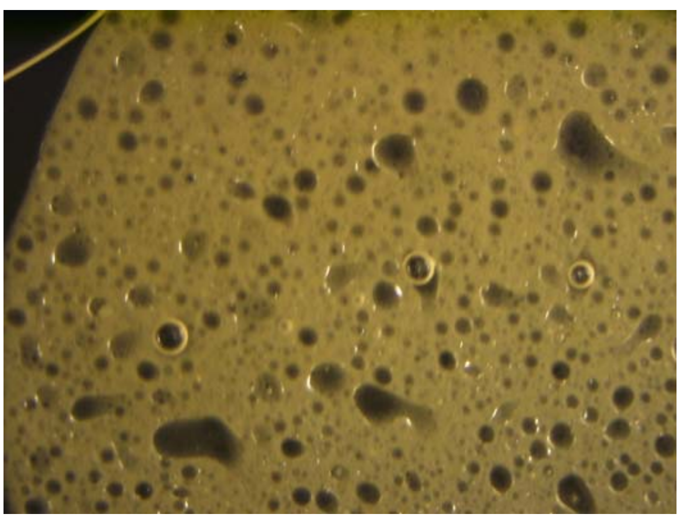
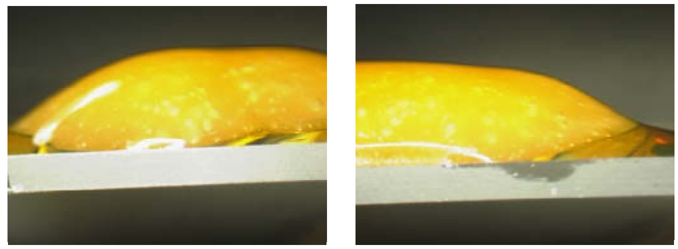


Fig. 9 – Microscopic examination of 50/50 dispersion of a crude oil and an aphron drilling fluid. Spheres are aphrons, while the dark, less-well-defined structures are oil droplets.

Compatibility of the drilling fluid and produced oils can also be determined by directly examining the wetting behavior of the two phases. As shown in **Fig. 10**, whether the oil is applied to the drilling fluid or the fluid applied to the oil, the applied phase spreads over the substrate phase, i.e. the contact angle is very low (< 5 degrees), indicating that the two phases are highly compatible.



(a) Displacement of Oil by Mud (b) Displacement of Mud by Oil

Fig. 10 – Aphron drilling fluids (opaque fluid) and crude oils (transparent fluid) are very compatible, as indicated by the low contact angles at the interfaces.

Viscosity of Aphron Drilling Fluids

The low-shear-rate viscosity of aphron drilling fluids is considerably higher than that of conventional reservoir drilling fluids, as shown in **Fig. 11**.

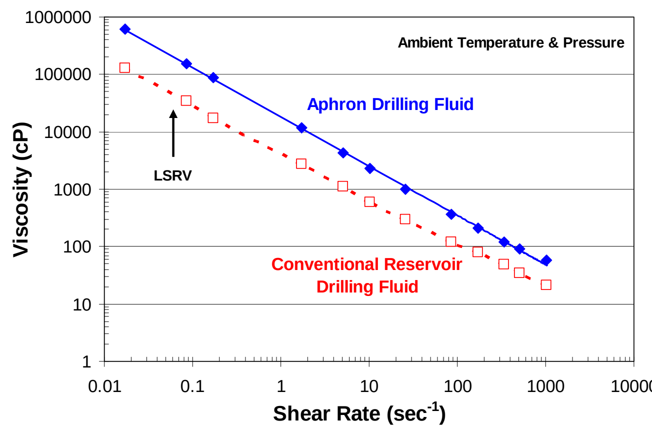


Fig. 11 – Aphron drilling fluids are power-law fluids, like conventional reservoir drilling fluids, but they possess significantly higher LSRV.

Here "LSRV" is designated as the viscosity at a shear rate of 0.06 sec^{-1}. The LSRV plays an important role in the invasion of aphron drilling fluids. As the fluid slows due to radial flow and bridging action of the aphrons, the shear rate decreases and the viscosity rises. This process continues until at some point the fluid essentially stops.

Flow through Porous Media

When tested in a radial flow simulator packed with beads, aphron drilling fluids clearly flow much more slowly than other solids-free reservoir fluids. As shown in **Fig. 12**, even an aphron drilling fluid containing very little air (aphrons) invades at a much slower rate than a high-performance reservoir drilling fluid. Addition of aphrons decreases the invasion rate even more.

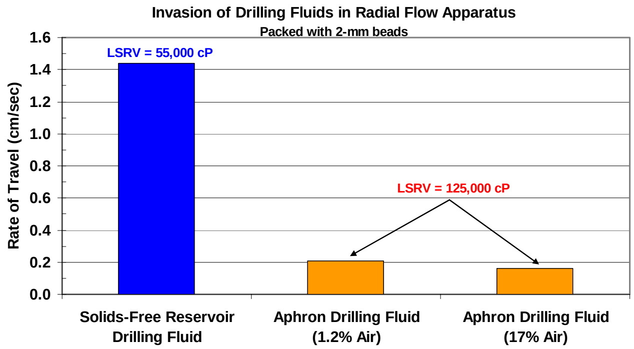


Fig. 12 – Aphron drilling fluids control fluid invasion into a packed bed significantly better than conventional reservoir drilling fluids.

Formation Cleanup and Completion

Return permeability, i.e. formation damage potential, of aphron drilling fluids approaches that of a high-performance reservoir drilling fluid. As shown in **Fig. 13**, even at permeabilities as high as 90 mD, aphron drilling fluids yield return permeabilities greater than 80%.

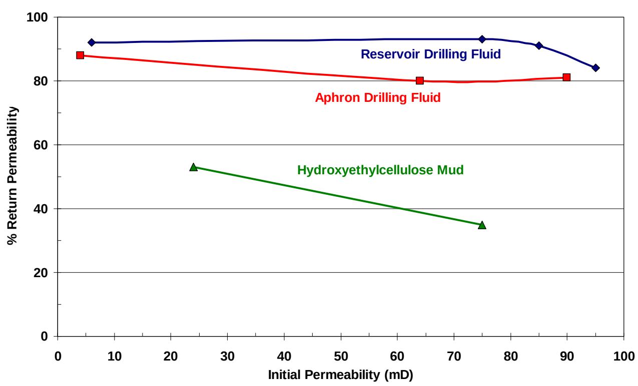


Fig. 13 – Aphron drilling fluids yield similar return permeabilities as high-performance reservoir drilling fluids. [Tests conditions: Berea sandstone, 150 °F, P_{inlet}=2500 psig, P_{outlet}=2000 psig, $P_{confining}$=3000 psig]

Examination of the back-flow of produced oils through a transparent aphron drilling fluid clearly shows that the oils channel through the drilling fluid (see **Fig. 14)**.

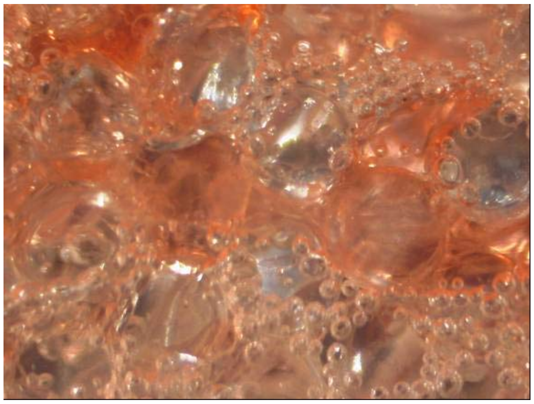


Fig. 14 – Channeling of a produced oil (red liquid) through transparent aphron drilling fluid (colorless liquid containing bubbles) in a packed bed of 2-mm glass beads.

However, very little back-pressure is necessary, and the channeling occurs as multiple streams throughout the cross-section of the simulated reservoir, rather than as a single stream.

Conclusions

Aphron drilling fluids control fluid invasion into permeable and fractured zones by two principal mechanisms. First, driven by a pressure differential and high shear rate, aphrons travel much faster than the base fluid and concentrate at the fluid front. Comminution of the aphrons by shear produces bubbles of a size similar to the openings in the rock. Bridging by aphrons, coupled with radial flow of the mud into the formation, decreases the shear rate dramatically; any particulate matter introduced into the mud is also expected to aid in this regard. As the fluid slows, the shear rate decreases and the viscosity rises. This process continues until at some point the fluid essentially stops.

Aphron drilling fluids also protect producing formations by minimizing loss of permeability (formation damage), first through the excellent compatibility of the drilling fluids with produced fluids, and second through the lack of affinity of aphrons for each other and for mineral surfaces.

Results of the laboratory investigation of aphron drilling fluids are consistent with field results and will help to reinforce the field applications of the fluid. These lab results support claims for the ability of aphron drilling fluids to:

- Serve as pneumatic fluids that can be recirculated and maintained as a conventional fluid.
- Provide properties of invasion control that are created within the rock and that are effective under downhole conditions.
- Create a micro-environment via bubbly flow and rapid growth of viscosity within the formation.
- Resist invasion with easy clean-up on completion, giving the operator faster access to production.
- Provide borehole stability hydrostatically and by minimizing wetting of the rock.
- Allow drilling of normal pressure and depleted zones simultaneously, which may lead to elimination of casing strings.
- Enhance cementing by allowing full circulation during cementing even across depleted zones.

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
mD	X 9.869233×10^{-16}	= m^2
psiga	X 6.895	= kPa
psig	+ 14.7	= psiga