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NEW INSIGHTS INTO APHRON DRILLING FLUIDS
(INVESTIGACION DE LOS MECANISMOS DE FLUIDOS DE PERFORACION DE AFRONES)

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ABSTRACT

Aphron drilling fluids have been applied worldwide to successfully drill depleted reservoirs and other high-permeability formations. Aphrons are specially designed air-filled bubbles that are usually incorporated into the fluid with conventional mud mixing equipment, thus reducing costs and safety concerns associated with air or foam drilling. Because the amount of air in the fluid is almost insignificant, the density of the fluid downhole is essentially that of the base fluid. Yet, the fluid is able to effectively seal loss zones and do so with minimal formation damage. Consequently, aphron drilling fluids are marketed as a cost-effective alternative to underbalanced drilling.

A study was initiated this past year to develop some understanding about the mechanisms by which these unique fluids can seal loss zones with little permanent formation damage. One key finding is that aphron drilling fluids seal loss zones via two mechanisms. First, the base fluid is very highly shear-thinning and possesses a low-shear-rate viscosity much higher than conventional reservoir drilling fluids. Furthermore, low thixotropy enables the fluid to generate high viscosity very quickly when entering a loss zone. Second, aphrons can survive substantial downhole pressures for a significant period of time. This feature enables low-density aphrons in a loss zone to migrate faster than the base liquid and concentrate at the fluid front to build an internal seal in the pore network of the rock. 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; therefore, they are expected to be produced back relatively easily, leaving little permanent formation damage.

The authors will discuss these findings and the impact they are expected to have in field operations.

INTRODUCTION

Many oil and gas reservoirs in the United States are mature and are becoming increasingly depleted of hydrocarbons, which makes for ever more 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] Uncontrollable drilling fluid losses are at times unavoidable in the often large fractures characteristic of these formations. Furthermore, pressured shales are often found interbedded with depleted sands, thus requiring stabilization of multiple pressure sequences with a single drilling fluid. Drilling such zones safely and inexpensively 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. The latter requires injection of a pill – a 50 to 100-bbl slug of fluid – that contains a high concentration of a plugging agent or a settable/cross-linkable fluid. However, none of these measures is always satisfactory, particularly clean-up of the reservoir to optimize production.

An increasingly popular alternative for drilling depleted or multiple pressure zones is the use of a fluid that has a density low enough to balance the pore pressure in the lowest-pressure zone. However, this results in drilling the zones above and below the depleted zone "underbalanced," a condition that risks wellbore collapse and blow-outs. A new drilling fluid technology was developed recently that does not entail drilling underbalanced, yet is designed to mitigate loss of fluid and differential sticking. This novel technology is based, in part, on the use of uniquely structured micro-bubbles of air called "aphrons."

Because of concerns over corrosion and well control, drillers generally discourage entrainment of air in drilling fluids; indeed, they often go to substantial lengths to eliminate air altogether from drilling fluids. Consequently, the purposeful incorporation of air, as in aphron drilling fluids, is looked on with some apprehension. 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 and helping to put these concerns to rest. In this paper we discuss the latest results of this study.

APHRON DRILLING FLUIDS

Aphron drilling fluids have been used successfully to drill depleted reservoirs and other low-pressure formations in a large number of wells, particularly in North and South America.[1] These novel fluids possess two chief attributes that serve to minimize fluid invasion and damage of producing formations. First, the base fluid is very shear-thinning and exhibits an extraordinarily high LSRV (Low-Shear-Rate Viscosity); the unique viscosity profile is thought to reduce the flow rate of the fluid dramatically upon entering a loss zone. Second, very tough and flexible microbubbles are incorporated into the bulk fluid with conventional drilling fluid mixing equipment. These highly stabilized bubbles, or “aphrons,” are believed to play a significant role in the sealing of the problem area by forming a seal within the permeable or fractured formation.

Aphrons are made of a spherical gas core and a protective outer shell.[5] In contrast to a conventional air bubble, which is stabilized by a surfactant monolayer, the outer shell of the aphron is thought to consist of a much more robust surfactant tri-layer. 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 to it. Under quiescent conditions, the structure is compatible with the aqueous bulk fluid; however, when enough shear or compression is applied to the aphron, e.g. when bridging a pore network, the aphron may shed its outermost shell layer, rendering the bubble hydrophobic.

Aphrons are claimed to act as a unique bridging material, forming a micro-environment in a pore network or fracture that appears to behave in some ways like foam and in other ways 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. Drilling fluid aphrons have cores of air and are constructed by entraining air in the bulk fluid with standard drilling fluid mixing equipment; this reduces the safety concerns and costs associated with high-pressure hoses and compressors commonly utilized in underbalanced air or foam drilling.[6] Although each application is customized to the individual operator’s needs, the drilling fluid system is generally designed to contain 12-15 vol % air at the surface, and the aphrons so generated are thought to be sized or polished at the drill bit to achieve a size of less than 200 µm diameter, 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 overall manner in which the drilling fluid is able reduce fluid losses downhole has been brought into question. As a result, there has been considerable resistance in some quarters to acceptance of the technology.

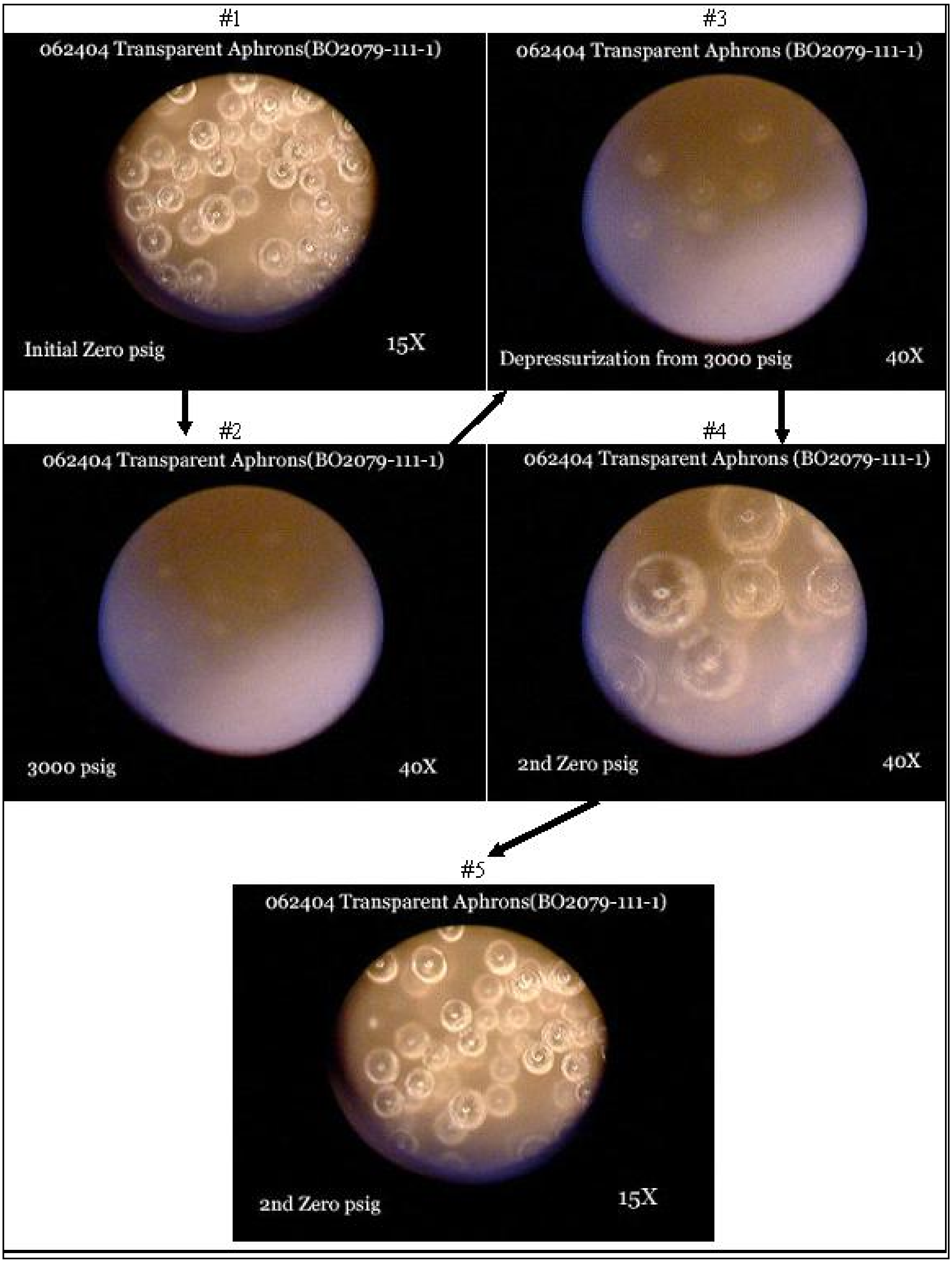
PROPERTIES OF APHRONS

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 27.7 MPa (4000 psig) 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 the modified Ideal Gas Law. 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 will reduce a bubble of 100 μm diameter at atmospheric pressure to 38 μm when subjected to a pressure of 1.8 MPa (250 psig), and 19 μm at 17.3 MPa (2,500 psig). But the biggest effect of pressure by far on the fate of a bubble is increased gas solubility. Henry’s Law and the Lewis-Randall rule state that the solubility of a gas is roughly proportional to the pressure.[7] For example, when a fluid containing 15% v/v entrained air at ambient pressure is compressed to 1.8 MPa (250 psig), all of the entrained air becomes soluble. If the stabilizing membrane surrounding the bubble is permeable, the air will diffuse into the surrounding medium and go into solution. This is indeed 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, in one aphron drilling fluid system, when subjected to a pressure of 1.8 MPa (250 psig), air is prevented almost indefinitely from diffusing out of the aphrons and into the aqueous medium.

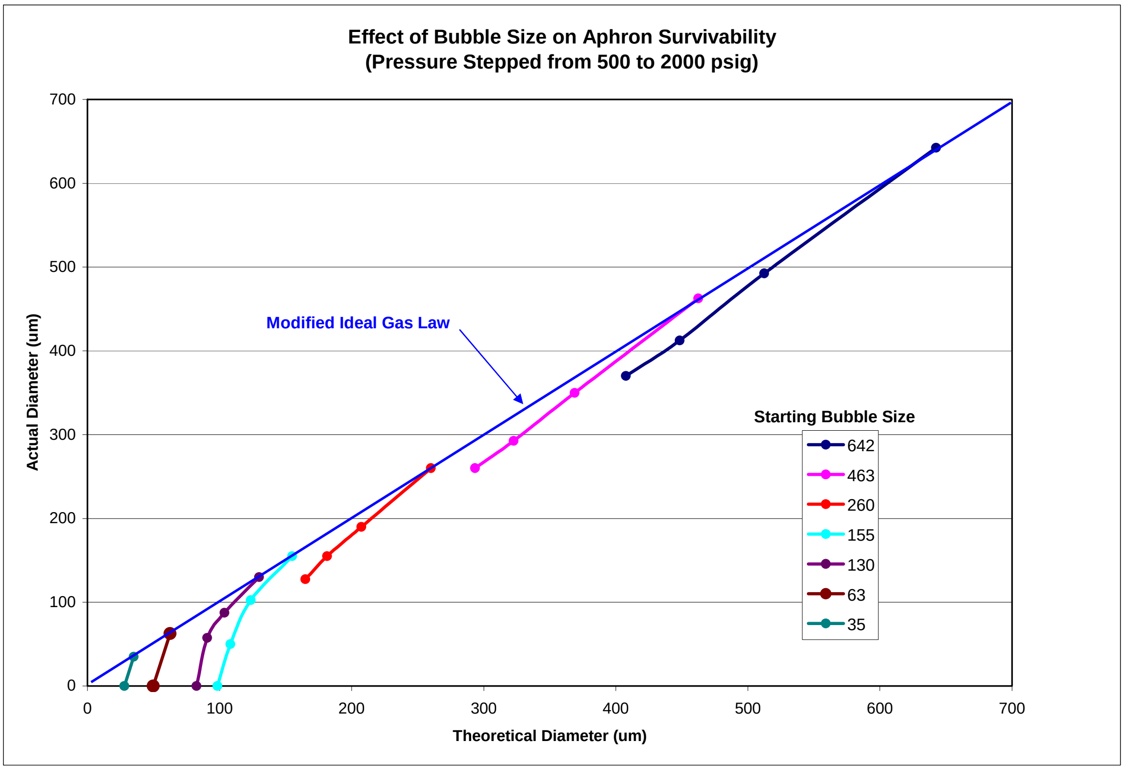
Over short periods of time, aphrons will survive compression and decompression. As shown in Figure 1, rapid compression of an aphron drilling fluid from 0 psig to 20.8 MPa (3000 psig) followed by decompression back to 0 psig results in essentially full regeneration of the aphrons.

Figure 1. Effects of Pressurization and Depressurization on Survivability of Aphrons



Large aphrons (> 100 μm diameter) appear to be able to survive much better than small aphrons. Figure 2 shows the effect of the size of an aphron on its survivability.

Figure 2. Effect of Size on Aphron Survivability



Aphrons of different sizes are pressurized from 3.55 MPa (500 psig) to 13.9 MPa (2000 psig) in steps of 3.45 MPa (500 psi). Large aphrons decrease in size with increasing pressure as expected by Boyle's Law (modified Ideal Gas Law); the small deviation from Boyle's Law 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] Upon decompression to a pressure sufficiently low for the aqueous medium to become supersaturated with air, the air is released; most of the air goes into existing aphrons, though it may also create new aphrons.

Another important finding is that the oxygen in aphrons – 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 nitrogen-filled aphrons. Thus, corrosion of tubulars and other hardware by aphrons is negligible. Figure 3 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.

FLUID DYNAMICS

The base fluid in aphron drilling fluids yields a significantly larger pressure loss (or, for a fixed pressure drop, lower flow rate) in long conduits than any conventional high-viscosity drilling fluid. Similarly, if flow is restricted or stopped, aphron drilling fluids (at a fixed wellbore pressure) generate significantly lower downstream pressures than do other drilling fluids. In permeable sands, the same phenomena are evident. In addition, in permeable sands of moderate permeability (up to at least 8 Darcy), aphrons themselves slow the rate of fluid invasion and increase the pressure drop across the sands. Lastly, and most importantly, aphrons move more rapidly through the sands than the base fluid.

Figure 3. Oxygen in Aphron Drilling Fluids is Depleted Rapidly

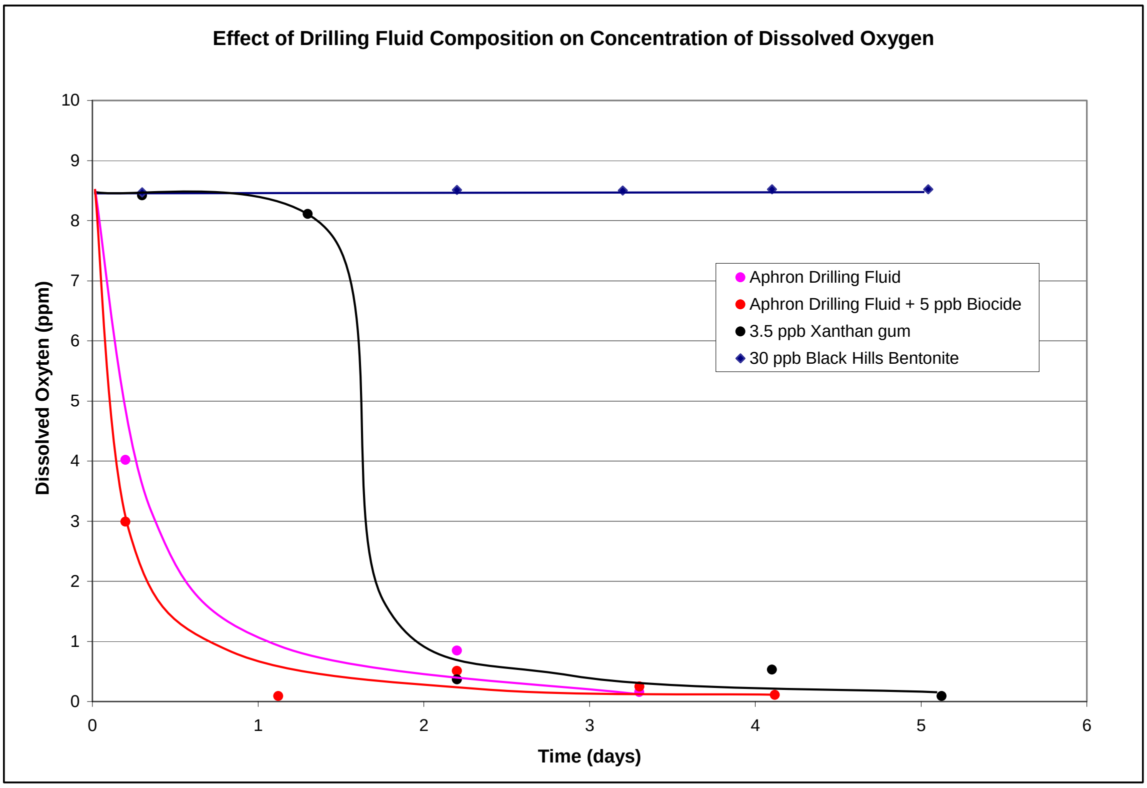
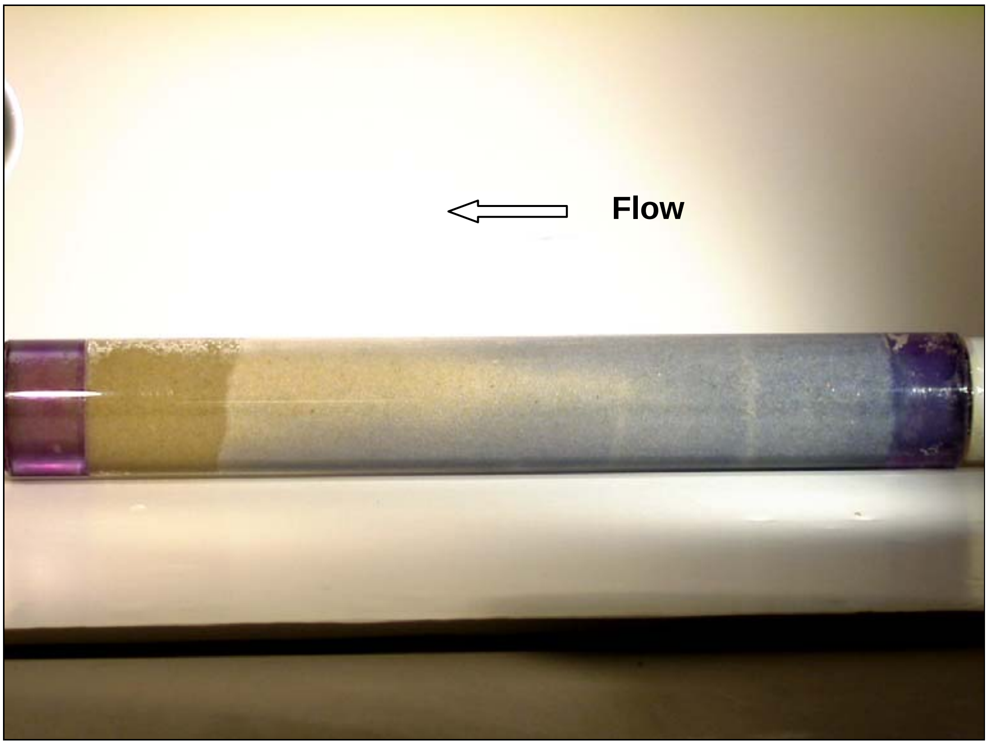


Figure 4 shows a transparent version of an aphron drilling fluid which has been dyed blue displacing water from a bed of 20/40 sand under the influence of a 0.69 MPa (100 psi) pressure gradient.

Figure 4. Bubbly Flow of Aphrons during Displacement by Aphron Drilling Fluid of Water from 20/40 Sand



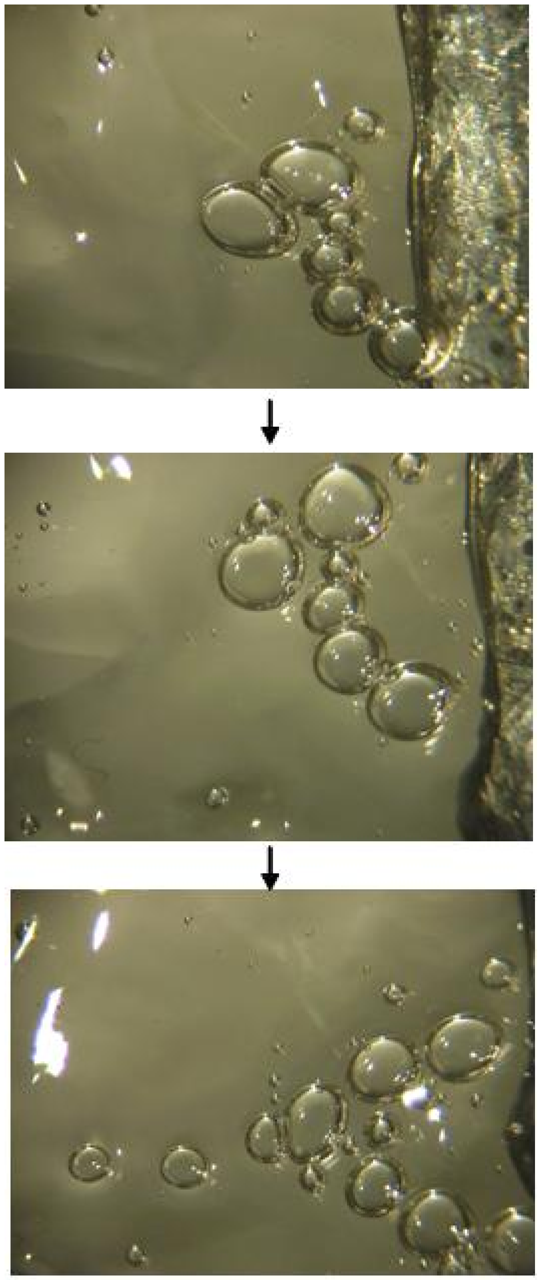
The drilling fluid front is populated with a high concentration of bubbles that turns the fluid nearly white. This phenomenon, called "bubbly flow," appears to follow conventional Navier-Stokes theory.[8] High-density particles such as barite (a densifying material) or drilled cuttings tend to be left behind the base fluid. Low-density internal phases, such as bubbles, flow more rapidly than the base fluid. For a rigid sphere in a fluid under the influence of a one-dimensional pressure gradient, $\Delta P/L$, 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.[9]

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 Figure 5, which shows bubbles that were purposely joined by creating them via air injection.

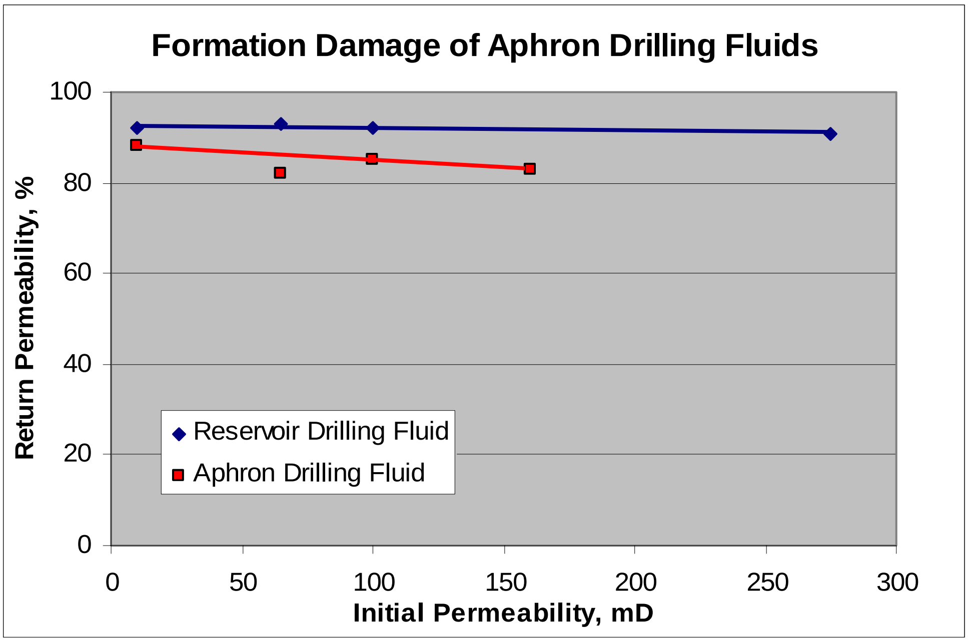
Figure 5. Aphrons Are not Attracted to Each Other or to Mineral Surfaces. Photos are Sequential.



The bond between the bubbles is thought to the result of imperfect development of the aphron shell. Within a few seconds, the bubbles separate from each other, rather than coalesce. 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.

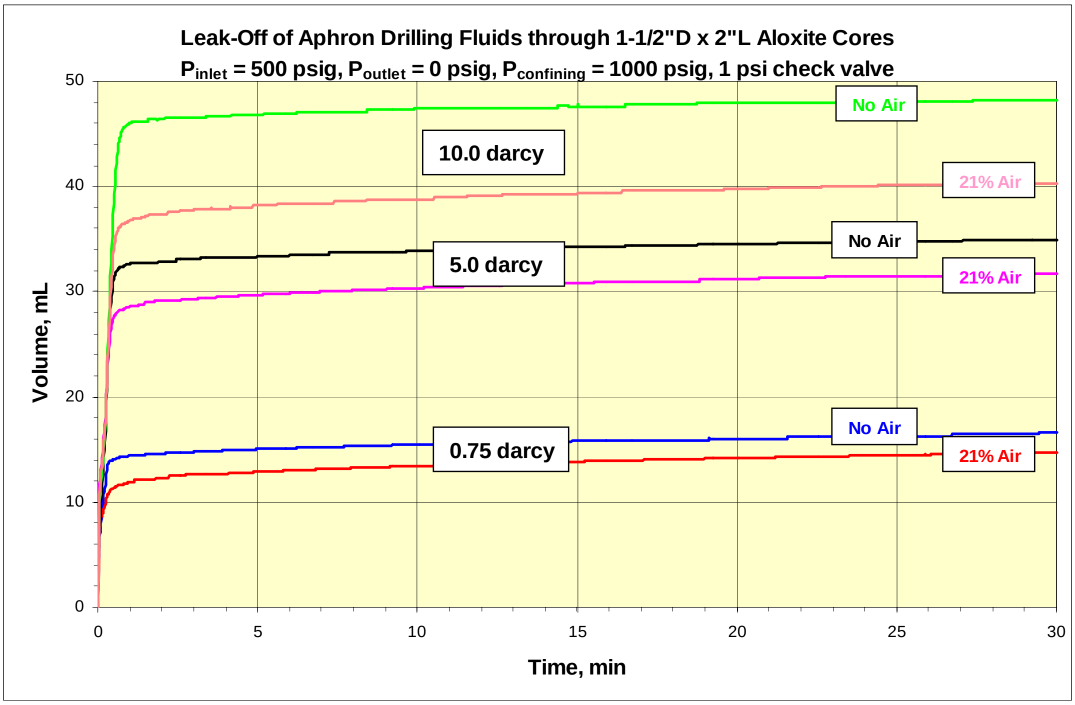
Return permeability tests carried out in Berea sandstone at 65.6 ^{o}C (150 ^{o}F), using inlet and outlet pressures of 17.3 MPa (2500 psig) and 13.9 MPa (2000 psig), respectively, indicate that the formation damage potential of this fluid is quite low and similar to that of a well-constructed reservoir drilling fluid (see Figure 6).

Figure 6. Return Permeability of Aphron Drilling Fluids is similar to that of Reservoir Drilling Fluids



Finally, static linear leak-off tests demonstrate that aphron drilling fluids are capable of sealing rock as permeable as 80 Darcy. Figure 7 shows some data for aphron drilling fluids in synthetic Aloxite cores with permeabilities of 0.75 to 10 Darcy. It is clear that the base fluid itself is primarily responsible for slowing or halting loss of the drilling fluid, but properly designed aphrons may reduce these losses even further.

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



CONCLUSIONS

Aphron drilling fluids possess two chief attributes that serve to minimize fluid invasion and damage of producing formations. First, the base fluid is very shear-thinning and exhibits an extraordinarily high LSRV (Low-Shear-Rate Viscosity) with very low thixotropy; this unique viscosity profile reduces the flow rate of the fluid dramatically upon entering a loss zone. Second, during fluid invasion in a permeable formation, 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 losses further. Aphrons are capable of carrying out this task by virtue of their high survivability at elevated pressures; conventional bubbles cannot do this. Furthermore, aphrons appear to have little affinity for each other or for rock surfaces, thereby enabling them to be produced back with relative ease.

TECHNICAL AND ECONOMIC CONTRIBUTIONS

Lost circulation is one of the most vexing and costly problems of many drilling operations. This is particularly true when drilling into depleted oil and gas reservoirs. Preventive measures currently focus on underbalanced drilling or use of a low concentration of a plugging agent in the entire circulating system. Remediation -- the most common alternative -- entails periodic injection downhole of a slug of plugging agent or settable/cross-linkable fluid. Underbalanced drilling is hazardous and costly, while the remediation agents are not only damaging to producing formations, they also are not always effective. Aphron drilling fluids are cost-competitive and especially effective at mitigating fluid invasion into depleted zones. These fluids use a combination of very high low-shear rheology to slow the progress of fluids through loss zones and specially constructed micro-bubbles (aphrons) to reversibly plug the loss zones. But little is known about the details of these processes in porous/fractured media at the elevated pressures encountered downhole. Developing some understanding of the physicochemical properties of aphron drilling fluids – and aphrons in particular -- under downhole conditions would help greatly to elucidate the roles played by the various components of the drilling fluids and provide guidance for optimization of the system.

This project was developed to provide much-needed laboratory data to demonstrate the efficacy of aphron drilling fluids, with the expectation that this would lead to greater application of aphron drilling fluid technology and reduce drilling costs.

BIBLIOGRAPHY

1. Montilva, J., Ivan, C.D., Friedheim, J. and Bayter, R.: “Aphron Drilling Fluid: Field Lessons From Successful Application in Drilling Depleted Reservoirs in Lake Maracaibo,” OTC 14278, presented at the 2002 Offshore Technology Conference, Houston, May 6-9, 2002.
2. Growcock, F.B., Simon, G.A., Rea, A.B., Leonard, R.S., Noello, E. and Castellan, R.: “Alternative Aphron-Based Drilling Fluid,” IADC/SPE 87134, presented at the 2004 IADC/SPE Drilling Conference, Dallas, Mar. 2-4, 2004.
3. Brookey, T., Rea, A. and Roe, T.: “UBD and Beyond: Aphron Drilling Fluids for Depleted Zones,” presented at IADC World Drilling Conference, Vienna, Austria, Jun. 25-26, 2003.
4. Growcock, F.B., Simon, G.A., Guzman, J., and Paiuk, B.: “Applications of Novel Aphron Drilling Fluids,” AADE-04-DF-HO-18, presented at the AADE 2004 Drilling Fluids Conference, Houston, TX, Apr. 6-7, 2004.
5. Sebba, F.: **Foams and Biliquid Foams – Aphrons**, John Wiley & Sons Ltd, Chichester (1987).
6. White, C.C., Chesters, A.P., Ivan, C.D., Maikranz, S. and Nouris, R.: “Aphron-Based Drilling Fluid: Novel Technology for Drilling Depleted Formations,” World Oil, vol. 224, no. 10 (Oct. 2003).
7. Perry, R. H. and Green, D.: **Perry’s Chemical Engineers’ Handbook**, 6th Edition, McGraw-Hill, 1984.
8. Landau, L. D. and Lifshitz, E. M.: **Fluid Mechanics (Course of Theoretical Physics, Vol. 6)**, 2nd Edition, Butterworth-Heinemann, 1995.
9. Popov, P.: Private Communication, Texas A&M University, March 1, 2005.

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