Enhanced Wellbore Stabilization and Reservoir Productivity with Aphron Drilling Fluid Technology

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Laboratory research is required to provide understanding and validation of aphron drilling fluid technology as a viable and cost-effective alternative to underbalanced drilling of depleted oil and gas reservoirs.

Many oil and gas reservoirs in the United States are mature and becoming increasingly depleted of hydrocarbons, which makes for 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. Uncontrollable drilling fluid losses are at times unavoidable in the often-large fractures characteristic of these formations. Furthermore, pressured shales often are found interbedded with depleted sands, thus requiring stabilization of multiple pressure sequences with a single drilling fluid. Drilling such zones safely and inexpensively is difficult with conventional rig equipment. Preventive measures with normal- or high-density fluids generally entail use of a low concentration of a plugging agent in the circulating system or remediation when the rate of loss of drilling fluid exceeds some threshold level. The latter requires injection downhole of a pill—a 50-bbl to 100-bbl slug of fluid—that contains a high concentration of a plugging agent or a settable/cross-linkable fluid. None of these measures is completely satisfactory.

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 blowouts. 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

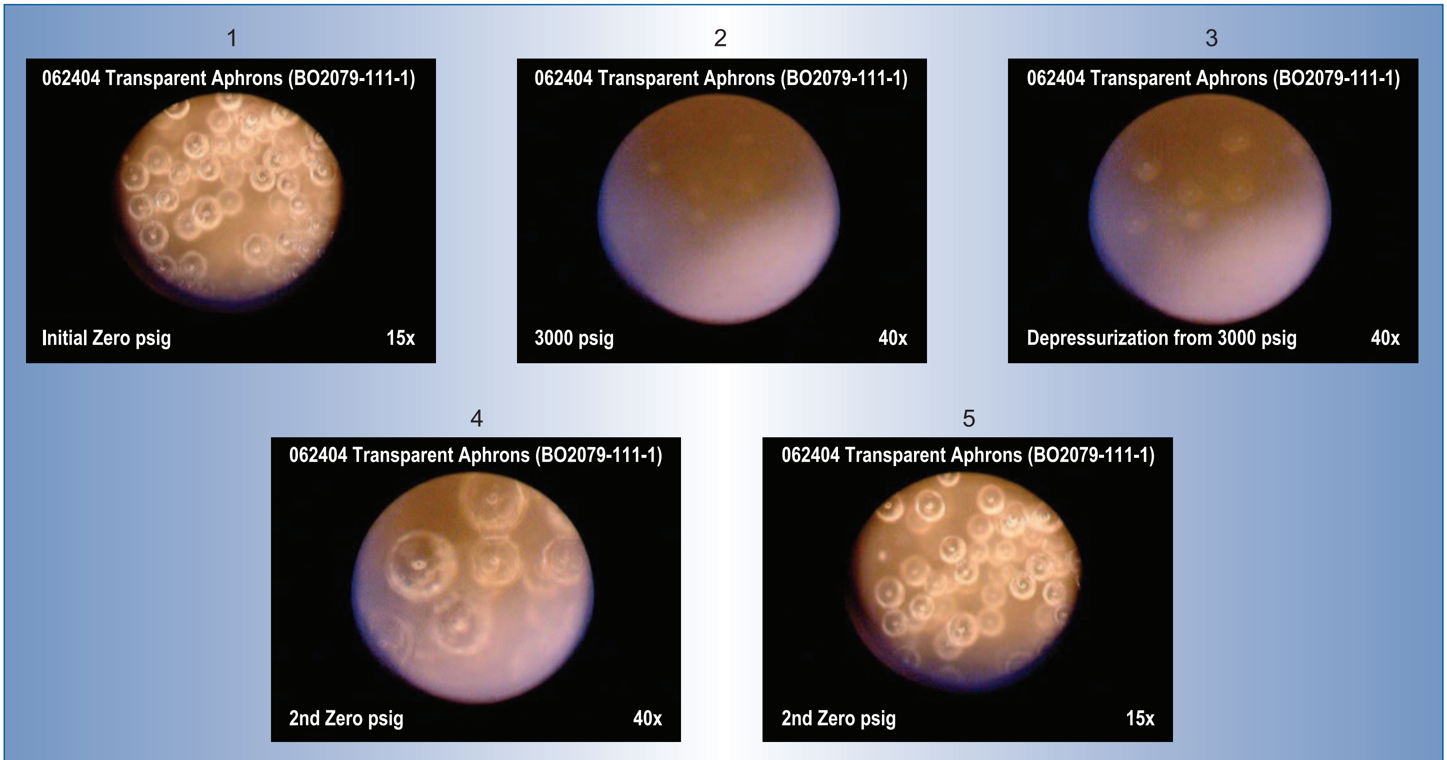

Figure 1. Aphrons can survive pressurization to at least 3,000 psig. Note that images 2 through 4 are magnified to 40x.

technology is based, in part, on the use of uniquely structured micro-bubbles of air called "aphrons."

Because of concerns about 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. Furthermore, there are no controlled studies that have been able to shed much light on the mechanism or the effectiveness of the aphrons at downhole pressures. This project was developed to provide the much-needed validation data that would put such issues to rest, thereby leading to greater application of aphron drilling fluid technology. With wider use of aphron technology, clients will reduce their drilling costs significantly and be able to pass some of those savings on to American consumers.

MASI Technologies, funded in part by the U. S. Department of Energy's Office of Fossil Energy, is carrying out a study with three objectives: develop a comprehensive understanding of how aphrons behave at elevated pressures and temperatures; measure the ability of aphron drilling fluids to seal permeable and fractured formations under simulated downhole conditions and establish how the fluids control fluid invasion with minimal formation damage; and determine the role played by each component of the drilling fluid.

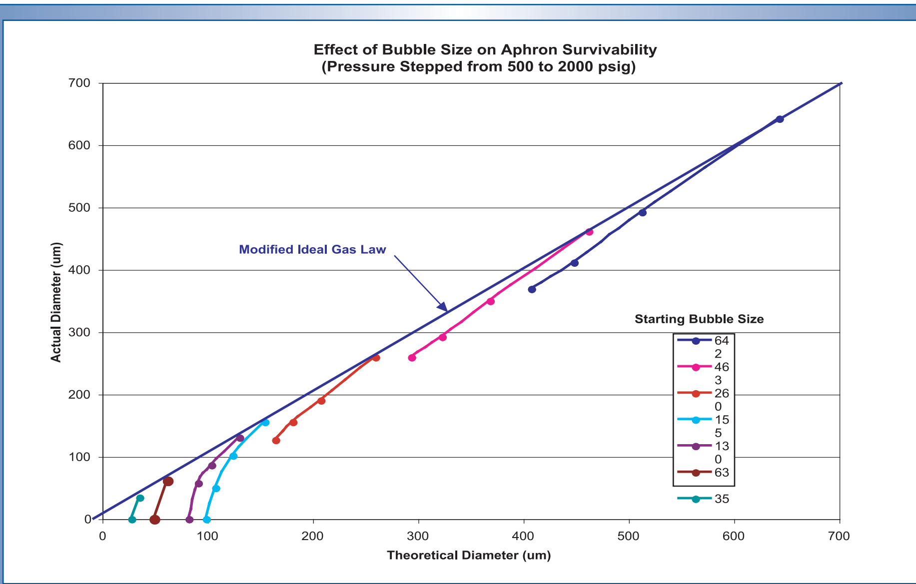

Figure 2. Large aphrons surove pressurization from 500 psig to 2,000 psig, but smaller aphrons (50 μm to 100 μm) do not.

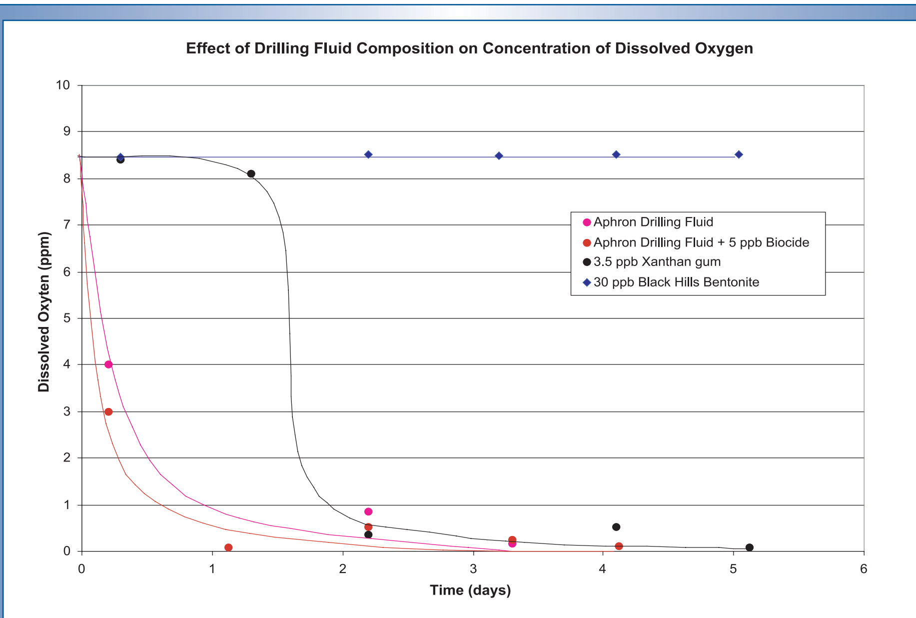

Figure 3. Oxygen in aphron drilling fluids depletes rapidly.

Background

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. These novel fluids have 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 low-shear-rate viscosity (LSRV); 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 essential to sealing the problem area and are thought to form a seal within the permeable or fractured formation.

Aphrons are made of a spherical gas core and a protective outer shell. Contrasting with 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, it is thought that when enough shear or compression is applied to the aphron, for example, when bridging a pore network, the aphron may shed its outermost shell layer, rendering the bubble hydrophobic.

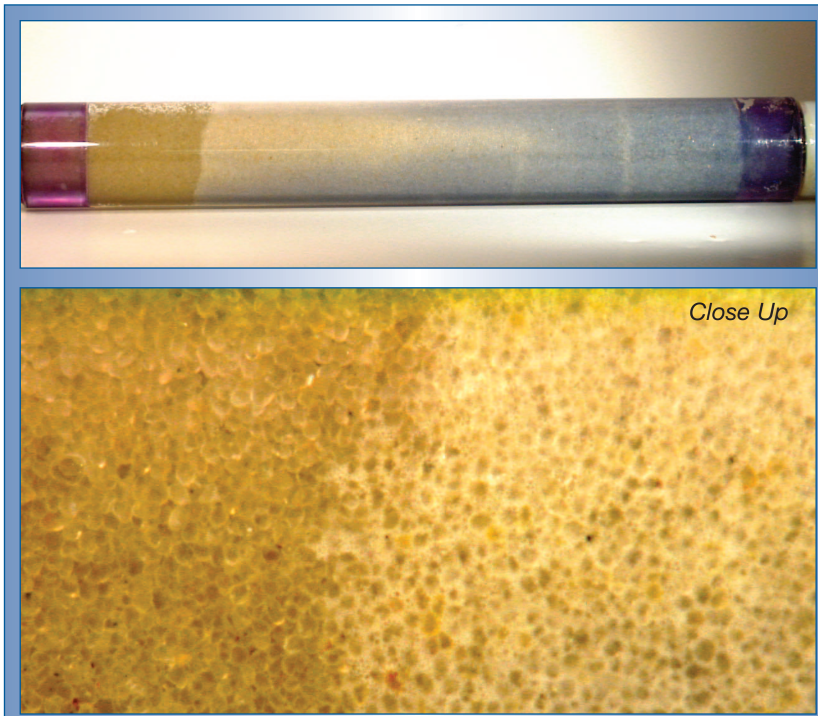

Figure 4. Aphrons undergo bubbly flow during displacement of water from 20/40 sand pack by an aphron drilling fluid. Note that the fluid front (at the fluid/water interface) is predominantly aphrons (white.)

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. Although each application is customized to the individual operator's needs, the drilling fluid system is generally designed to contain between 12 vol % and 15 vol % air at the surface (ambiant temperature and pressure), and the aphrons generated are thought to be sized or polished at the drillbit to less than 200 µm diameter, which is typical of many bridging materials.

The project is divided into two phases. Phase I (year 1) dealt with developing evidence for the ways in which aphrons behave differently from ordinary surfactant-stabilized bubbles, particularly how they seal permeable and micro-fractured formations during drilling operations. Various methods were evaluated for characterizing the properties of aphrons, including acoustic bubble spectrometry, optical and electronic micro-imaging and interfacial tension. Key properties investigated included the effects of pressure on bubble size, the influence of environmental parameters on aphron stability, the affinity of aphrons for each other and the mineral surfaces in rock pores and micro-fractures, and the nature of aphron seals in permeable and micro-fractured rock. Initial sealing and formation damage tests were carried out, using lab-scale apparati designed to simulate permeable and micro-fractured environments. Phase II (year 2) is focusing on optimization of the structure of aphrons and composition of aphron drilling fluids, quantifying the flow properties of the fluids (radial vs. linear flow, shear and extensional viscosity effects and bubbly flow phenomena), and understanding formation sealing and damage under simulated downhole conditions (including scale-up tests), so as to furnish irrefutable evidence for this technology and provide field-usable data.

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 to reduce fluid losses downhole has been brought into question. As a result, there has been considerable resistance in some places to acceptance of the technology.

Aphron properties

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 27.3 MPa (4,000 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 200-µm diameter at atmospheric pressure to 76 µm when subjected to a pressure of 250 psi,

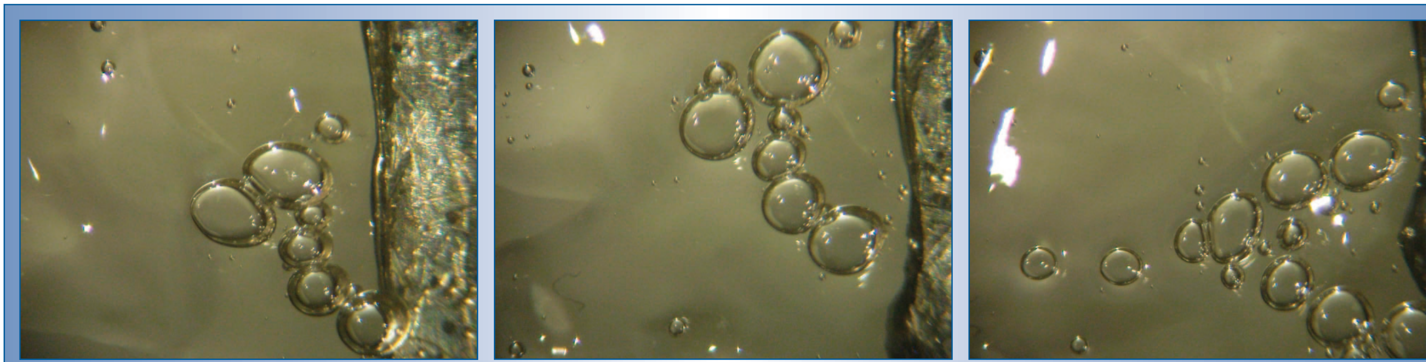

Figure 5. In time, conjoined aphrons separate and show little affinity for each other.

and 36 μm at 2,500 psi. But the biggest effect of pressure by far on the fate of a bubble is increased gas solubility. Henry's Law states that the solubility of a gas is roughly proportional to the pressure. When a fluid containing 15% v/v entrained air at ambient pressure is compressed to just 250 psi, all of the 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 what happens with ordinary bubbles, and it occurs within a matter of seconds after compression. Aphrons have a much less permeable membrane, so they do not lose their air as readily; indeed, when subjected to a pressure of 250 psi, air is prevented almost indefinitely from diffusing out of the aphrons and into the aqueous medium.

Aphrons will survive compression and decompression for short periods of time. As shown in Figure 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. Large aphrons appear to be able to survive better than small aphrons. Figure 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 every 10 seconds. Aphrons (larger than 200 μm diameter) decrease in size with increasing pressure as expected by Boyle's Law (modified Ideal Gas Law); the small deviation from Boyle's Law is because of loss of air via slow diffusion into the surrounding fluid. When aphrons reach a critical minimum size (50 μm 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. 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—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) and low pressures, 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 4 shows a transparent version of an aphron drilling fluid (dyed blue) displacing water from a bed of 20/40 sand under the influence of a 100-psi pressure gradient. The drilling fluid front is populated with a high concentration of bubbles that turn the fluid nearly white. This phenomenon, called "bubbly flow," appears to follow conventional Navier-Stokes theory. 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:

$$V = 0.23\ r2/\mu m * \Delta P/L$$

where r is the bubble radius and μm is the fluid viscosity. For flow through permeable media, the expression is modified to incorporate Darcy flow.

Wettability tests indicate 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 purposely joined by creating them via air injection. The bond between the bubbles is thought to be 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.

Finally, leak-off tests demonstrate that aphron drilling fluids are capable of sealing rock as permeable as 80 Darcy. Figure 6 shows test results in synthetic Aloxite cores of 0.75 Darcy to 10 Darcy permeability. The base fluid in aphron drilling fluids is primarily responsible for slowing or stopping the invasion, but properly designed aphrons can reduce these losses even further.

Future efforts

Phase II of this Project is continuing with a study of the effects of individual components in the fluid on the properties of aphrons; a detailed investigation of the surface chemistry involved in the interactions of the drilling fluid with reservoir rock and produced fluids; visualization of the flow of aphron drilling fluids in a wellbore/reservoir simulator; and extension of the fluid flow model to include bubbly flow. ✧

Acknowledgements

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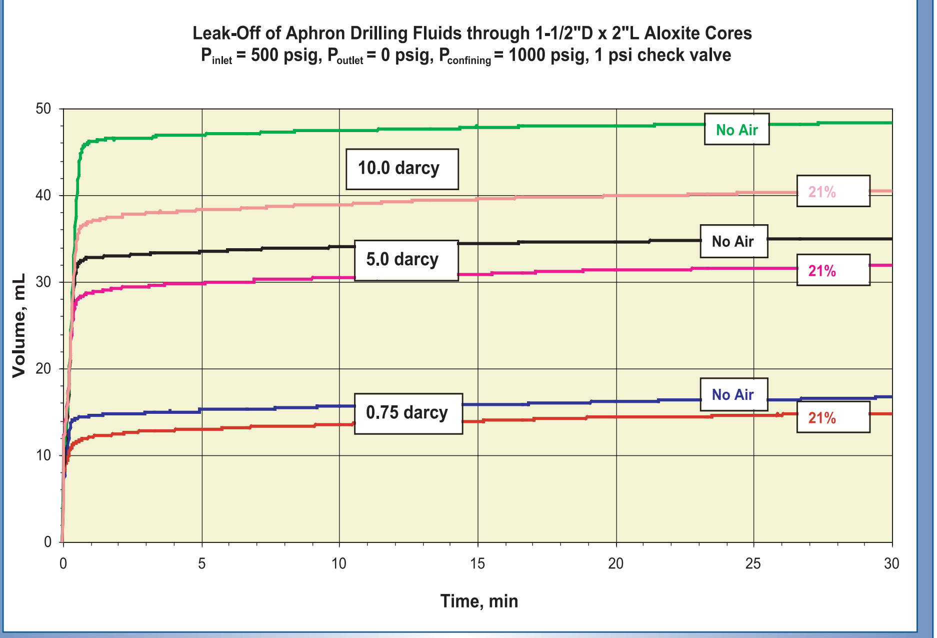

Figure 6. Static linear leak-off tests of aphron drilling fluids in permeable Aloxite cores demonstrate the sealing performance of the fluids and the role played by aphrons (air).