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Alternative Aphron-Based Drilling Fluid

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Abstract

A novel drilling fluid containing specially designed micro-bubbles -- “aphrons” – was recently introduced and has now been employed successfully in various parts of the world to drill through formations which previously had experienced uncontrollable losses and high incidence of differential sticking. The aphron-laden fluid appears to be particularly well suited for drilling through depleted zones. Wellbore stabilization is accomplished by (a) greatly reducing the invasion rate of the base fluid with additives that minimize the thixotropy of the fluid and enhance its shear-thinning character, and (b) reversibly plugging pores and fractures by the aphrons.

A recent innovation has permitted modification of the original fluid design to permit incorporation of selected clays in the fluid for rheology control and stabilization of the aphrons. In addition, the chemistry of the aphron membrane has been altered using a polymer/surfactant package so that the longevity and resistance to pressurization of the bubbles are greatly improved.

The authors will discuss the design and properties of the new Alternative aphron-based drilling fluid and how these characteristics can be used to advantage in a drilling operation.

Introduction

Aphron-based fluids have been used successfully to drill depleted reservoirs and other low-pressure formations in a large number of wells in North and South America.[1] They are considered a viable choice in place of drilling underbalanced for avoidance of whole fluid loss and differential sticking in low-pressure zones and multiple-pressure sequences, such as pressured shales interbedded with depleted sands.

Aphron-based drilling fluids possess two unique characteristics that enable them to reduce fluid invasion into permeable or microfractured formations. A highly shear-thinning fluid with flat gels slows its flow rate markedly when entering a low-shear loss zone. Complementing this effect is the incorporation of highly flexible but tough microbubbles of air -- “aphrons” -- that function as a unique lost circulation material which can reversibly plug pores and fractures. The aphrons are generated using conventional fluid-mixing equipment, which obviates the need for compressors, high-pressure hoses and connections that are required for conventional air or foam drilling and which add costs and safety concerns to the drilling operation.[2]

Standard aphron-based drilling fluids rely on the use of polymers to generate their unique rheological profile and enhance the toughness of the aphrons. Recently a system was developed that uses clays, along with some polymers, to provide the desired rheological profile and stabilize the aphrons. In this paper, we describe some characteristics of aphron-based drilling fluids in general with specific emphasis on features of this Alternative aphron-based drilling fluid.

Physical and Chemical Characteristics of Aphrons

Aphrons are initially incorporated into a drilling fluid using conventional mud-mixing equipment, which entrains air up to a level dictated by the concentration of aphron-generating surfactants. As is the case for any bridging material, the resulting concentration and size distribution of the aphrons play important roles in how well they seal a permeable formation or fracture. Generally, the system is engineered to incorporate 12 to 15% v/v air at the surface, though this may be adjusted as necessary. This moderate concentration of air minimizes viscosity effects and avoids operational problems like pump cavitation. Air concentration is determined from the density of the fluid, while the bubble size distribution is determined via Acoustic Bubble Spectrometry, a technique which enables analysis of opaque fluids.[3-5] Under ambient conditions, aphrons typically range in size from about 15 to 100 μm in diameter.

A drilling fluid aphron is composed of a core of air that is stabilized by a polymer/surfactant shell. In contrast to a conventional bubble, which is stabilized only by a surfactant monolayer, the shell of an aphron consists of a trilayer of surfactants.[6] As indicated in the rendition in **Fig. 1**, the inner surfactant film is overlayed with a sheath of viscosified water and a double layer of surfactants that renders the aphron hydrophilic and compatible with the continuous aqueous phase of the mud. However, the surfactants in the double layer are not strongly associated; under sufficient shear or compressive forces, the outermost surfactant layer will be shed and will leave a structure with residual hydrophobic character.

Aphrons are stabilized primarily by (a) controlling the collision rate among the bubbles, thus reducing the probability of coalescence, and (b) controlling the properties of the aphron shell. The collision rate can be minimized by maximizing the viscosity of the bulk fluid. Thus the use of a highly shear-thinning base fluid not only minimizes fluid invasion into the loss zone, but it also minimizes interaction of the bubbles in the wellbore.

The properties of the aphron shell that appear to be most important for stabilization of the bubbles include toughness and permeability. Toughness is defined here as resistance to pressurization/depressurization. Permeability is defined as the ease with which water from the shell and air from the core escape the bubble. Toughness and permeability of the shell are thought to be controlled, at least in part, by the thickness[6] and viscosity[6,7] of the shell. A thick, viscous shell will counter the tendency for water to diffuse into the bulk liquid (the "Marangoni effect")[6-8] and for the shell to become excessively thin and rupture, e.g. during expansion into a low-pressure zone.

Thickness and viscosity of the aphron shell also are important for controlling loss of air into the bulk fluid. The amount and rate of loss of air are governed by the air concentration gradient across the aphron shell and solubility of air in the bulk fluid. As pressure increases, e.g. as the drilling fluid makes its way downhole, both the concentration gradient of air across the aphron shell and solubility of air in the bulk fluid increase proportionately. When an aqueous fluid containing 15% v/v air under ambient conditions (15 psia) is subjected to a pressure of 150 psia, compression alone will reduce the volume of entrained air to about 1.5% v/v. However, the solubility of air in fresh water at that pressure is about 15 cm^3/g water (approx. 15% v/v), *i.e.* at 150 psia, all of the air could potentially dissolve in the bulk fluid. The process is rapid, too. Diffusion of air from conventionally stabilized bubbles into the bulk fluid occurs in a fraction of a second.[9] Properly designed aphrons appear to resist pressurization and to lose air much less easily than conventional bubbles. Experiments conducted in a visualization cell indicate that aphrons can survive up to at least 1500 psia for extended periods of time, in accord with density measurements at elevated pressures.[3] Not only do aphrons survive above 150 psia, they also do not achieve the small size expected from compression. It is thought that the aphron film is sufficiently tough and impermeable that it resists compression and suppresses transport of air to the aqueous environment.

Thickness and viscosity of the aphron shell are controlled by the nature of the surfactant and viscosifier that are incorporated into the shell. In a conventional aphron-based drilling fluid, the viscosifier is a polymer. In the Alternative system, the viscosifier is a polymer-clay blend.

Reducing Drilling Fluid Losses with Aphrons

The hydrophobic nature of the aphron shell enables aphrons to clump together, yet resist coalescence. During invasion of an aphron-laden drilling fluid into a formation (**Fig. 2**), aphrons are forced together to form large aggregates and create a structure of deformed cells in the pore throats or fracture tip akin to that of a true foam. This structure possesses the same hydrophobic character of the individual aphrons.[6]

In water-wet reservoirs, capillary pressure resists intrusion of hydrophobic materials into capillary restrictions in the formation. Before a bubble can be displaced, the pressure differential across the bubble must be sufficient to overcome the capillary pressure.[10] The cumulative resistance of many bubbles in a capillary restriction is expected to be so large that it is unlikely that pressure gradients encountered in the field would be enough to overcome it.[11]

The effectiveness of the seal formed by aphrons is dependent on the size of the pore throats/fracture and the degree of hydrophobicity of the aphron shell. Small openings and strongly hydrophobic bubbles promote sealing. Conversely, if the pore throats/fractures are too large or the shell of the aphron is not hydrophobic enough, a very high pressure may be required for the bubbles to aggregate and form an effective seal.

Drilling Fluid Composition and Standard Properties

Tables 1a and 1b show the composition of typical unweighted Standard and Alternative aphron-based drilling fluids, both of which consist of a viscosifier, pH control additives, aphron generator, aphron stabilizer and fluid-loss-control additives. The major difference between the two systems is the nature of the viscosifier. For the Standard system, all mud components are initially mixed with a single-spindle mixer. For the Alternative system, however, the shear rate afforded by this type of mixer is too low to yield the clay and a Silverson L4R mixer is used to mix all mud components. For both types of muds, air is entrained using a Silverson L4R Mixer running for 6 min at 7,000 rpm.

All of the additives have been chosen to meet Gulf of Mexico and Canadian environmental regulatory requirements. With the exception of the aphron enhancer, which is awaiting approval, all other additives are expected to be acceptable for use in the North Sea.

Standard and Alternative freshwater aphron-based drilling fluid samples were prepared in the lab using the formulations shown in **Table 2**. Standard API rheology (Fann 35 viscometer), LSRV (Brookfield viscometer, L3 spindle, 0.06 sec^{-1}) and "Half-Life" (3 hr) were measured at 70°F and 120°F prior to and after hot-rolling at 150ºF for 16 hr. The Half-Life of the entrained air under ambient conditions is a rough measure of the stability of the aphrons. The procedure for calculating Half-Life is given in **Appendix A**.

The mud properties measured at 70ºF after heat-aging are displayed in Table 2. The rheological profile of the Alternative system is only a little different from that of the Standard system. The over-all rheological profile of the Alternative system is somewhat lower, as is aphron stability (Half-Life), and fluid loss is twice as great. In saltwater systems the differences are more remarkable. The Alternative system has a much flatter (shear-independent) profile, so that high-shear rheology is much lower than for the Standard system. Indeed, saltwater versions of the Alternative system display Fann 35 profiles that are nearly independent of shear rate, so that viscosity is approximately inversely proportional to the shear rate. Fitting the 6 and 100-rpm data to a Power Law or

Herschel-Bulkley model yields an n-value of almost zero. On the other hand, saltwater Alternative systems also tend to be more thixotropic, producing more progressive yet fragile gels.

Sealing and Formation Damage Potential of Alternative Aphron-Based Drilling Fluid

Leak-Off tests were conducted in a Triaxial Loading Core Leak-Off Tester, a schematic of which is shown in **Fig. 3**. An abbreviated procedure is given in **Appendix B**. Some test results at low pressure using freshwater muds in 10-Darcy 1½-in. diameter x 2–in. length Aloxite cores are shown in **Figs. 4 and 5**. These figures show the Leak-Off as a function of time, including the dead volume ahead of the core. Correcting for this dead volume, which is approximately 25 mL, gives net Leak-Offs after 30 min of 43 and 20 mL for the Standard and Alternative air-free aphron-based mud samples. With air, *i.e.*, with aphrons, the difference is even more impressive: 37 and 8 mL, respectively. Other tests, using slightly modified formulations of those muds in fresh water, bay water (2% salinity) and seawater, showed even more effective sealing of 10-Darcy cores (**Table 3**). Again, the Alternative system exhibited lower total net Leak-Off and a more substantial effect of aphrons than observed for the Standard system. One reason for the latter, however, is that the high-shear imposed on the Alternative system to entrain air and comminute the bubbles also increases dispersion of the clays, thereby increasing bulk fluid viscosity and reducing fluid invasion even more.

Return permeability tests were conducted with a dynamic return permeability apparatus, shown in **Fig. 6**. In this system, the aphron mud is subjected to a 500-psi pressure drop (2500 psig/2000 psig) and then raised back up in pressure to 2500 psig before initiating the Leak-Off phase of the test. As shown in the test procedure described in **Appendix C**, the fluid is flowed past the face of the core during the Leak-Off phase. The results obtained with a moderate-permeability Berea sandstone at 150ºF are summarized in **Table 4**, which shows that the Standard and the Alternative aphron-based drilling fluids gave return permeabilities of 80% and 85%, respectively. For comparison, a typical reservoir drilling fluid can be expected to give a return permeability on the order of 90% under these conditions. Highly damaging muds, on the other hand, such as hydroxyethylcellulose (HEC)-based fluids, give return permeabilities of 25 to 40% in this test. Thus, both aphron-based drilling fluids may be considered to have low formation-damage potential.

Properties of Alternative Aphron-Based Field Muds

A seawater Alternative aphron-based field mud was recently run offshore Mexico. The rheological profile observed for the mud was demonstrably flatter than for other seawater-polymer-based muds previously used in the area; indeed, the mud was perceived as providing excellent hole cleaning and low ECD and possessing generally good handling characteristics. At this time, the data remain confidential to the operator and are unpublishable. Nevertheless, the observed performance of the Alternative aphron-based system has resulted in the operator specifying it on the next ten (10) wells in that field.

Summary

- Both the Standard (polymer-viscosified) and Alternative (clay-viscosified) aphron-based drilling fluids are capable of controlling mud losses in high-permeability media effectively. Indeed, total Leak-Off in permeable cores tends to be lower for the Alternative system.
- Formation-damage potential in sandstone of moderate permeability is as low for the Alternative aphron-based drilling fluid as it is for the Standard system.
- The very low high-shear viscosity of saltwater Alternative aphron-based drilling fluids results in low equivalent circulating density and minimizes wellbore stability problems.
- Despite lower low-shear viscosity, neither phase separation nor reduced aphron stability have been noted in Alternative aphron-based drilling fluids.

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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
psia	+ 14.7	= psi = psig

Appendix A – Half-Life of Entrained Air

The Half-Life method serves as a simple way to determine bubble stability of aphron-based drilling fluids. The calculation assumes that the rate of loss of undissolved air follows standard first order kinetics, as in the case of a true foam. Although aphrons are better characterized as dispersed bubbles rather than foams and their rate of decay is not strictly first order, experience indicates that the Half-Life is a fair trend indicator of bubble stability.

First determine the "initial" amount of undissolved air incorporated in the mud, or Air Quality, using the following expression:

$$\% \text{ Air}_i = [(d_t - d_i)/d_t] \text{ x } 100$$

where d_t is the theoretical density of the air-free mud and d_i is the initial density after the aphron generation step.

Determine the "final" amount of undissolved air incorporated in the mud after some arbitrary period of time, e.g. 3 hr, 24 hr:

$$\% \text{ Air}_f = [(d_t - d_f)/d_t] \text{ x } 100$$

The rate coefficient for loss of air from the mud, K_{Air}, is given by

$$K_{Air} = (t_f - t_i)^{-1} \ln (\% \text{ Air}_i/\%\text{Air}_f) = (1/24) \ln (d_t - d_i)/(d_t - d_f)$$

where d_f is the "final" mud density after the desired waiting period. Note that the Half-Life for decay of the Air Quality, $\tau_{1/2}$, is simply equal to

$$\tau_{1/2} = \ln 2 / K_{Air} = 0.693/K_{Air}$$

$$\text{or} \quad \tau_{1/2} = 16.63 \text{ x } \ln^{-1} (d_t - d_i)/(d_t - d_f) \text{ in hr}$$

Appendix B – Leak-Off Test Procedure

1. Saturate core with water.
2. Mount core in hassler cell and apply confining stress to 500 psi above system pressure.
3. Raise oven temperature to bottomhole temperature for the formation core.
4. Raise system pressure via accumulator to desired pressure.
5. Open accumulator to allow for injection to core.
6. Treat core for 30 min with aphron-based drilling fluid, monitoring effluent volume vs time.

Appendix C – Return Permeability Test Procedure

1. Saturate core with 10% by weight NaCl brine.
2. Mount core in Hassler cell and apply confining stress to 3000 psig
3. Raise system pressure to 2000 psig.
4. Raise core temperature to 150° F.
5. Flow low-toxicity mineral oil (formation to wellbore) and establish initial permeability of core.
6. Apply a 500-psi pressure drop on aphron-based drilling fluid by flowing from one transfer vessel set at 2500 psig to another transfer vessel set at 2000 psig through a back pressure regulator. Maintain system pressure at 2000 psig.
7. Treat core for 3 hr with aphron-based drilling fluid at 500-psi overbalance, monitoring effluent volume vs time. This is a dynamic treatment with the drilling fluid circulating across core face.
8. Repeat step 5 to determine return permeability, returning flow of low-toxicity mineral oil from formation side of system to wellbore side of system.

Table 1a - Formulation of a Typical Standard Aphron-Based Drilling Fluid System

Component	Function	Concentration
Fresh water/brine	Continuous phase	0.97 bbl
Soda ash	Hardness Buffer	3 lbm/bbl
Biopolymer blend	Viscosifier	5 lbm/bbl
Polymer blend	Filtration Control Agent and Thermal Stabilizer	5 lbm/bbl
Alkalinity Control Agent	pH control	0.5 lbm/bbl
Surfactant Blend	Aphron Generator	2 lbm/bbl
Biocide	Biocide	0.05 gal/bbl
Polymer/Surfactant Blend	Aphron Stabilizer	1 lbm/bbl
Polymer*	Mud Conditioner	1 lbm/bbl
Oligomer*	Defoamer	As Needed

*Optional component

Table 1b - Formulation of Typical Alternative Aphron-Based Drilling Fluid System

Component	Function	Concentration
Fresh water/brine	Continuous phase	0.97 bbl
Soda ash	Hardness Buffer	0.25 lbm/bbl
Caustic Soda	Alkalinity Control Agent	1.5 lbm/bbl
Clay/Polymer Blend	Viscosifier	25 lbm/bbl
Polymer Blend	Filtration Control Agent and Thermal Stabilizer	2 lbm/bbl
Surfactant Blend	Aphron Generator	0.5 lbm/bbl
Biocide	Biocide	0.05 gal/bbl
Polymer/Surfactant Blend	Aphron Stabilizer	1 lbm/bbl
Polymer*	Mud Conditioner	0.2 lbm/bbl
Oligomer*	Defoamer	As Needed

*Optional component

Table 2. Standard Properties of Standard and Alternative Aphron-Based Drilling Fluids

Additive	Standard	Alternative
Formulation		
Fresh Water (mL/lab bbl)	338	331
Soda Ash (g/lab bbl)	3.0	0.3
Caustic Soda (g/lab bbl)		1.5
Biopolymer Blend (g/lab bbl)	5.0	
Polymer Blend (g/lab bbl)	5.0	
Clay/Polymer (g/lab bbl)		25.0
Polymer Blend (g/lab bbl)		2.0
Alkalinity Control Agent (g/lab bbl)	2.0	
Aphron Generator (g/lab bbl)	1.0	0.5
Shale Inhibitor (g/lab bbl)	1.0	0.2
Aphron Enhancer (g/lab bbl)	1.0	1.0
Properties		
600-rpm Dial Reading	94	84
300-rpm Dial Reading	78	63
200-rpm Dial Reading	70	53
100-rpm Dial Reading	60	42
6-rpm Dial Reading	39	23
3-rpm Dial Reading	36	22
PV (cP)	16	21
YP (lb/100 ft^2)	62	42
Gel, 10-sec (lb/100 ft^2)	39	30
Gel, 10-min (lb/100 ft^2)	58	46
LSRV (0.06 sec^{-1}) (cP)	192,000	130,000
API Fluid Loss (mL/30 min)	7.1	14
Half-Life (hr)	152	108

Table 3 - Net Leak-Off
$P_{confining}$ = 2500 psig, P_{inlet} = 100 psig, P_{outlet} = 0 psig, 10-Darcy Aloxite 2-in. length x 1½-in. diameter, 77°F

Aphron-Based Drilling Fluid	Aqueous Medium	Leak-Off (mL/30 min)	
		No Air	15% Air
Standard	Fresh Water	29	21
Alternative	Fresh Water	22	10
Standard	Bay Water*	27	5
Alternative	Bay Water*	22	7
Standard	Sat. NaCl	32	12
Alternative	Sat. NaCl	20	14

* 2% Salinity

Table 4. Formation Damage Potential
$P_{confining}$ = 3000 psig, P_{inlet} = 2500 psi, P_{outlet}=2000 psi, Berea sandstone 2-in. length x 1-in. diameter, 150ºF

Aphron-Based Drilling Fluid	Initial Permeability (mD)	Leak-Off,* (mL)	% Return Permeability	Break-through Pressure (psi)
Standard	64	43	80	119
Alternative	72	90	85	50

* Total effluent volume at 500-psi overbalance after 3 hr

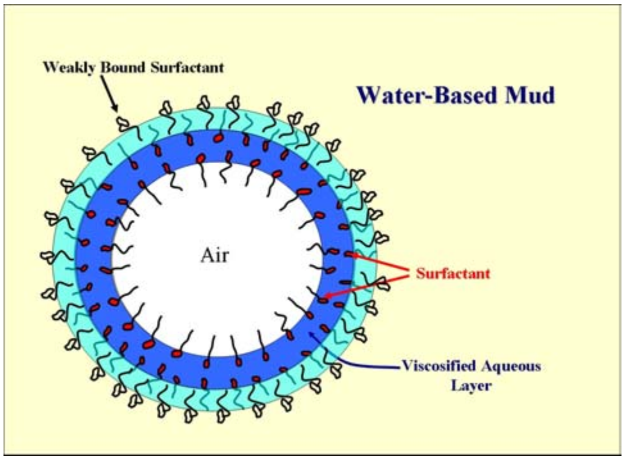

Fig. 1. Schematic of an Aphron

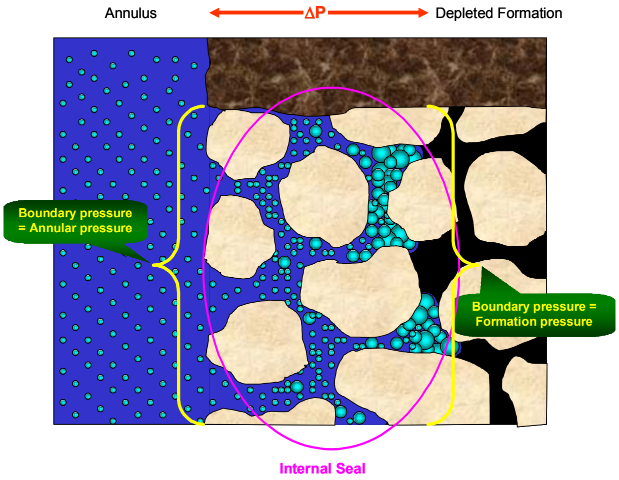

Fig. 2 - Invasion of Aphron-Based Drilling Fluid into Permeable Zone.

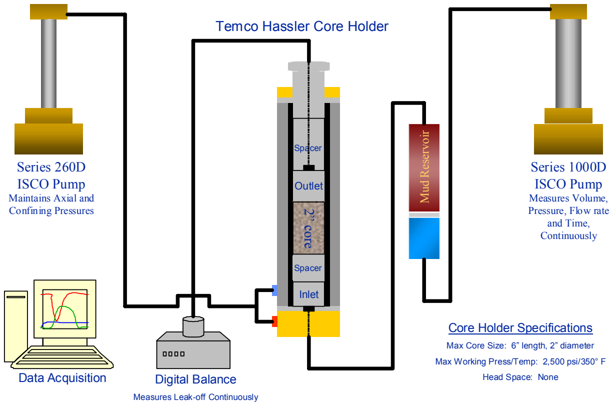

Fig. 3 - Triaxial Loading Core Leak-Off Tester.

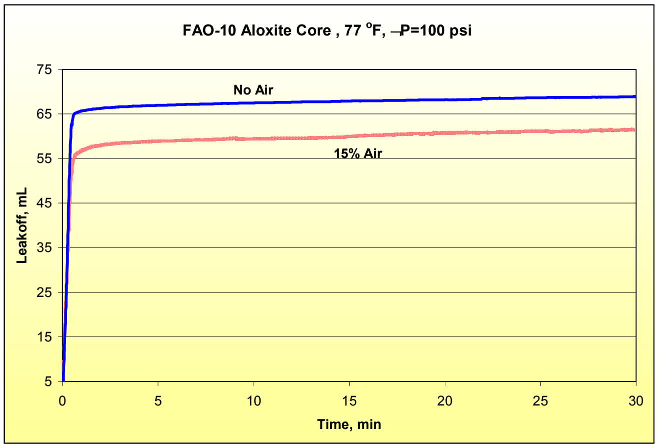

Fig. 4 - Leak-Off Test with Standard Aphron-Based Drilling Fluid

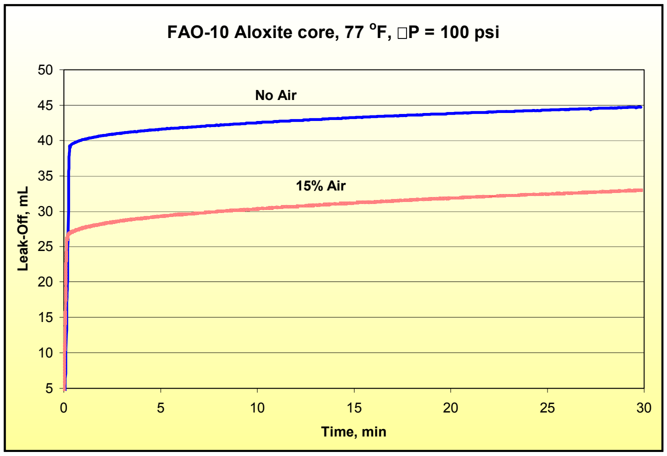

Fig. 5 - Leak-Off Test with Alternative Aphron-Based Drilling Fluid.

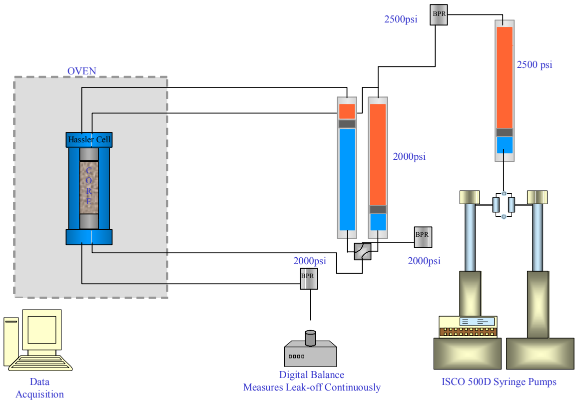

Fig. 6 - Dynamic Return Permeability Tester