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"Micro-Bubbles": New Aphron Drill-In Fluid Technique Reduces Formation Damage in Horizontal Wells

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Abstract

Horizontal drilling technology has enhanced production through increased ability to expose formation openings. In most cases, these openings are fractured, vugular, or otherwise highly permeable. Many are drilled through low-pressure reservoirs where drilling fluid losses occur and often cause severe formation damage. The use of conventional lost circulation control materials are restricted due to the downhole tools required, and borehole sealing techniques are mostly ineffective in this type of application.

A novel new drill-in fluid is being used to drill horizontal and high angle wells through these damage-prone reservoirs. This fluid combines certain surfactants and polymers to create a system of "micro-bubbles" known as aphrons[1] encapsulated in a uniquely viscosified system. These aphrons are non-coalescing and recirculateable so that density reduction is accomplished without expensive air or gas injection.

A unique feature of the micro-bubble network, stopping or slowing the entry of fluids into the formation, creates downhole bridging. The unique viscosity builds to create a resistance to movement into and through the zone so that a true noninvasive, at-balance fluid is achieved. Test data shows the enhanced hole cleaning and suspension properties.

Case histories show that drilling problems are reduced, mud losses are prevented, and completions are simplified. Natural production was achieved in many cases. No problems with formation damage or inhibited production were seen.

At-Balance Drilling

Much has been written about underbalanced drilling and it has been successful in many areas. Injection of compressed air or nitrogen is usually necessary to accomplish the density reduction needed to achieve underbalanced conditions. Air drilling and foam systems are also used in underbalanced drilling. These techniques are used to provide enhanced penetration rates, prevent or minimize lost circulation, and to reduce formation damage due to invasion of drilling fluids or filtrate. The use of expensive, hard to get air compressors and injection equipment or nitrogen generators is required. In addition, many problems are experienced using these systems including well control, borehole instability, unpredictable fluid properties, drillstring corrosion, and difficulty using downhole directional tools.

At-balance drilling techniques are used to produce a fluid density that is near the formation pressure gradient, yet is not so low that formation fluids enter the borehole. The density of the at-balance fluid is kept higher than the formation pressure yet low enough that it does not exceed that required to force drilling fluids into the rock.

A new at-balance technique uses "micro-bubbles" that are non-coalescing and recirculateable to produce densities lower than that of water. These unique bubbles, called "aphrons", are made to occur within the mud system without injecting external air or gas. Aphrons in this case exist as independent spheres with a gas or air core encapsulated by a multiple layer film[fig 1]. This film is the key to maintaining the bubble strength that allows the aphrons to function as a stable density reducing mechanism. A surfactant is used to produce the surface tension to contain the aphron as it is formed, build the multi-layer bubble wall, and create interfacial tension to bind the aphrons into a network capable of creating downhole bridging[fig 2].

In order to be most effective, the aphrons must be stabilized in a drilling fluid. This is most effectively done by using a high yield stress, shear thinning (HYSST) polymer. This type of polymer most effectively viscosifies the "lamella"[1] separating the aphrons and the water layer in the bubble film surrounding the aphron core[fig 3]. This builds the strength of the bubble film and the surrounding layer so that aphrons are self-contained. This feature allows them to resist both compression and expansion so they are effective downhole and recirculateable. According to Sebba[1], aphrons protected by encapsulating shells can attract one another to build up complex aggregates. These aggregates can contain tremendous energy because of Laplace pressure[fig2].

A Xanthan biopolymer was found to be most effective in stabilizing the aphrons in drilling fluids. The low shear rate viscosifier (LSRV) was used to produce excellent hole cleaning, cuttings suspension, and invasion control in addition to aphron stability. Table shows the ability of aphrons to enhance LSRV.

Aphrons are unique in structure and size. The typical aphron ranges from 10-100 microns in diameter. This allows them to be recirculated even while solids control systems are in use. Most will not be removed even by fine screen shale shakers or flowline cleaners, and since they have little mass, they are retained even in hydrocyclones or high speed centrifuges. Aphrons do not interfere with downhole tools such as MWD or mud motors making them ideal for directional and horizontal applications. Aphrons have many characteristics beneficial to drilling, completion, and workover fluids (see Table 2).

In order to produce aphrons, a gas core of the proper size and conditions must exist. The aphrons must be generated under conditions of pressure drop and cavitation. These conditions exist in the hydrodynamic cavitation produced as the drilling fluid exits the bit nozzles. This turbulence and pressure drop creates "microvoids" that are available to be encapsulated by the surfactant and harnessed as energized spheres able to contain the pressure under which they are created. With this contained energy aphrons have the ability to reduce density, create downhole bridging in formation openings, and enhance LSRV.

Rheological Parameters

In addition to stabilizing the aphrons, the drilling fluid must produce hole cleaning, cuttings suspension, and invasion control necessary for optimum performance while drilling the high angle or horizontal borehole. The ability of LSRV systems to produce this performance has been well documented by Powell[2], Carico[3], Sehuelt[4], and Beck[5]. The importance of maintaining sufficient polymer concentration to optimize these benefits is described by Powell as critical polymer concentration (CPC)[6]. Field measurement of the rheological properties is described by Bloodworth[7]. Since LSRV must be measured by viscometers such as the Brookfield, which is not readily available in most field applications, relaxation measurement is a crucial tool in practical applications. The most effective way to determine HYSST rheology with a Fann 35A is to evaluate the 6 and 3 rpm readings and gel strengths. The 6 and 3 rpm readings should be elevated and close, the initial gel should be elevated, with the 10 minute gel no more than 1 ½ times the initial gel, and the 30 minute gel should approximate the 10 minute gel reading. Relaxation measurement (RM)[7], is required to indicate CPC. As a rule of thumb, the 3 rpm and initial gel Fann readings should be at least 10, and the RM after 5 minutes should be at least 1/3 the initial gel. Table 1 shows a typical formulation with properties from the HYSST viscosifiers and the increase in LSRV after incorporating aphrons. Table 7 shows the increase in LSRV with continued generation and the stability of the aphrons with time. Table 6 shows the stability of the HYSST polymers in brines and the potential density reduction.

The drilling performance of the HYSST fluids in high angle and horizontal hole cleaning, and its prevention of cuttings bed formation, invasion control has been documented. This cleaner borehole reduces cuttings and debris, which can be carried into the formation or stored in the cuttings bed. A decline in production sometimes is caused by the mobilization of debris caused by cleanup or stimulation treatments, and often by production itself. This is especially true where a screen or slotted liner is set, and the debris plugs the openings, restricting production.

Filtrate Control

Filtrate control is thought by many to be a key element in controlling formation damage. The job of a non-damaging fluid is undoubtedly that of controlling the movement of mud, solids, or filtrate into the formation. A primary role of the HYSST system is that of stopping invasion by creating a viscous resistance to flow. This viscous mechanism should be such that water is tied up and the mechanical and capillary forces of invasion are overcome. In order to complete the invasion control and minimize penetration of the formation, many favor the creation of a filter cake using solids to bridge at the formation openings. This filter, or wallcake is effective in controlling losses to permeable sands or small openings, and less effective in stopping losses to fractured or vugular zones. The principle of the filtrate mechanism is to use solids packing at the openings, and thus build an external barrier by augmenting with starches and certain filtrate control polymers.

In the HYSST system, the aphrons are capable of acting as the bridging solids in the filtrate mechanism. The aphrons bridge and pack off at the formation openings of a permeable zone, but unlike conventional solids, they are also capable of adjusting to bridge a fractured or vugular opening. These aphron bridging agents also have an additional advantage in that they have a low density, and do not increase formation overbalance. They are also readily removed when hydrostatic pressure is released, and do not usually require cake lift-off techniques.

Some instances are documented where PAC is detrimental to the LSRV system[8]. Use of CM starches were described in this application for effective filtrate control. The CM starches were not only effective in reducing filtrate in this system, but were found to enhance the LSRV properties themselves.

Another filtrate control material used in the HYSST system is an oligosaccharide thermal stabilizer (TS) able to effectively control filtrate as shown in Table 3. TS is also able to enhance and stabilize the LSRV properties at temperature, Tables 4 and 5. Notice the complete control of spurt loss which is considered by some to be the most damaging of all fluid characteristics in this application. Notice also the increase in intermediate shear rate viscosity as shown by the 100 rpm Brookfield reading and the thixotropic index (.5 rpm/100 rpm). Strictly LSRV fluids are at a disadvantage in stopping movement where rates are high enough to produce shear such as sometimes happens where large fractures or vugs are encountered. This can be remedied by increasing the intermediate shear rate viscosity without creating high gels or plastic viscosity. This combination of LSRV and intermediate shear rate viscosity (ISRV) invasion control, aphron bridging, and the filtration control TS should provide optimum formation protection for high angle and horizontal wells.

Microbiological Control

Stability of the LSRV properties is crucial to maintaining invasion control, a clean wellbore, and aphron stability. Since the HYSST polymers are organic, they are subject to biodegradation by microbiological activities. These are described by Ezzat, et al[9]. These polymers were found to be subject to sulfate reducing bacteria (SRB), general aerobic bacteria (GAB), and anaerobic bacteria. In addition to the destruction of invasion control properties, another formation damage concern was raised, that of the potential for biomass plugging in the formation.

Although many engineers maintain that high salinity and/or high pH prevent the bacterial activity, there is some evidence that certain areas of the system can harbor bacterial presence even under conditions of salinity and high pH. Because these polymer systems are rarely run at high salinity or pH, they are especially at risk of microbiological attack.

Even though many prefer to wait until evidence of bacteria is seen, the better program is to be proactive in treating with sterilizers and biocides to prevent any microbe presence in the drilling fluid or in the formation.

Currently used biocides include aldehydes, isothiazolones, and quaternary phosphonium salts[9]. The programs run with the HYSST and aphron system used gluteraldehyde supplemented with isothiazolones. Initial treatment was with about 2,000 ppm aldehyde. The residual was monitored and maintained at least at 300 ppm. Periodic supplements of isothiazolone were used since some early wells detected bacteria even though a residual of aldehyde was present. This indicates that a combination biocide is sometimes required. Phenol red cultures should be inoculated and monitored on a consistent basis to be sure the biocide program is adequate, and to allow early intervention.

In addition to the biocide program outlined, a field practice of sterilizing the makeup water was used. This was done by adding “bleach” (7% sodium hypochlorite) to the makeup water before adding to the system. It is important to understand that the hypochlorite is an oxidizer, and can be harmful if added directly to the polymer system. Since it is readily spent upon addition to the water, additions can be made soon after treating the water once oxidation is complete. Most water can be adequately sterilized by additions of 1 gallon of bleach to each 100 barrels of makeup water.

Solids Control

Any drill-in fluid must be kept clean. Solids damage to sensitive producing zones is well known. The HYSST/aphron system is easily kept clean. Because of the polymer encapsulation, drilled solids are preserved and readily removed at the surface. Flocculants are compatible and can be used to enhance the removal of fines that could not be separated by mechanical means. The aphrons exist as small, low-density particles, which pass through fine screens and are not removed by centrifugation. No compromise in the solids removal system is required in order to accommodate bridging and sealing materials, as is the case in some other drill-in fluids.

The most effective drilled solids removal program using this system is a high-speed fine screen shaker or flowline cleaner, and a centrifuge combined with a chemical flocculation program. Using this method, solids can be kept at a very low level, with a thin, tough, effective wallcake.

Corrosion Control

Corrosion is generally a major problem when drilling with aerated muds. The presence of high concentrations of air creates a condition of extreme corrosion where air and water are in constant contact with the drillstring. This corrosive condition is usually aggravated where polymer systems and salts are used due to the lower pH and acceleration of corrosion due to salts.

Underbalanced drilling can also allow the intrusion of corrosive gases such as CO_2 and H_2S. This can create a requirement for extensive corrosion control programs. Many times severe corrosion results even with the most extensive programs. In addition, underbalanced drilling cannot be conducted safely where high concentrations of H_2S are present.

The application of at-balance drilling techniques provides control of these dangerous, corrosive gases. It also allows the application of a general inhibitor such as phosphate ester. The use of filming amines is discouraged where they are added directly to the mud system since they can affect the surface chemistry of the aphrons. The application of filming amines by spraying drillpipe on trips may be used with little effect on the aphrons.

Oxygen scavengers cannot be used with the aphron system since the availability of air is necessary for aphron formation. The scavenger is not necessary to corrosion protection since any air is quickly encapsulated and held inside the surfactant/polymer shell. This isolates the air from drillstring contact and negates the corrosive attack.

Field experience with the HYSST aphron system has shown no indication of excessive corrosion rates or instances of pitting. The combination of a moderate pH (9.0-10.5) and application of phosphate ester is the best approach to corrosion control. Several wells were run with no corrosion inhibitor and showed acceptable rates as well.

Case Histories

1. The first application of the aphron system was in West Texas where a horizontal re-entry was drilled in the Fusselman. The build section was drilling with a xanthan system when a large fracture was drilled (the bit dropped 1 foot) and complete returns were lost. With the bit near bottom, aphrons were generated. As soon as the aphrons left the bit, pump pressure began to increase indicating the fluid was being lifted. Returns were regained on bottoms up, and drilling resumed. Aphrons were generated throughout the remainder of the well with no further losses.

Mechanical problems with the small tools used in the re-entry caused the project to be abandoned before productive intervals were penetrated. Hole conditions were excellent, however, with no drag, fill, or instability. Formation invasion was controlled even when large fractured openings were exposed.

2. Two projects were drilled into a dolomitic reef zone of North Texas. This zone was considered difficult to drill since the openings are large and lost circulation is severe. The projects were planned using the HYSST aphron system. Both were drilled successfully with no losses. Invasion was controlled even in the zone of interconnected large vugs. Drilling conditions were excellent and no problems were experienced.

The wells were both completed openhole with no treatment, and full production was established within 24 hours. Drilling fluid recovery was minimal.

3. A Monterey shale re-entry was drilled to a planned 750-foot departure. The Monterey shale is highly fractured and unstable. The HYSST aphron system was maintained with an 8.0 ppg fluid to control invasion while providing borehole stability.

Drilling conditions were good, and no problems were experienced in drilling or running the slotted liner to TD. Minimal drilling fluid was recovered and the well was put on production with no treatment required.

4. A Sisquoc sand well was drilled with a 1,000 ft lateral. The Sisquoc is an unconsolidated, permeable sand easily damaged by mud and filtrate invasion. Invasion control is required not only for good production, but to avoid instability while drilling. The zone was drilled with the HYSST aphron system and the slotted liner was run with no problems. The well was put on production with a minimal recovery of drilling fluids.

Subsequent treatments were required after the liner was plugged with “tar balls” produced from the zone. No problems were experienced with drilling fluid damage, however.

Several more horizontal and high angle wells have been drilled with the HYSST aphron system. All have exhibited excellent drilling conditions and no instances of formation invasion or damage were seen.

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Table 1

Effect of Aphron Generation on Low Shear Rate Viscosity (LSRV) of Various Fluids

Fluid Sample No.	1	2	3	4	5	6
Low Shear Rate Viscosity, cp (Brookfield Rheology @ 0.5 rpm)						
Before Aphron Generation	880	4,560	1,880	11,600	5,280	1,380
After Aphron Generation	4,880	9,200	6,200	19,400	11,600	20,600

Procedure:

-Hand mix in aphron generating material and run initial LSRV

- Follow by generating aphrons and measuring final LSRV

Table 2

Characteristics of Aphrons in Drilling, Completion and Workover Fluids

- **Definition:** Aphrons are highly stable, micron-sized gas bubbles
- **Size range**: Sub-micron to 100 microns
- **Composition**: Can be composed of any type gas
- **Difference:** Aphrons are not foam
- Aphron fluids as opposed to foam are recirculatable
- Aphron fluids do not require injection of gases in order to generate the micro-bubbles
- Aphrons require some minimum Low Shear Rate Viscosity (LSRV) for stability
- The minimum Low Shear Rate Viscosity depends on system makeup
- Aphrons will enhance the Low Shear Rate Viscosity
- Aphrons will lower the fluid density during pressure drops
- Aphrons act as temporary, deformable solids and can provide non-damaging seals

Table 3

Typical Properties of Aphron Based Fluids

Fluid No.	1	2	3	4	5	6	7	8
Composition								
Fresh Water, bbl	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
LSRV Viscosifier, lb	1.5	1.5	1.5	1.5	2.0	2.0	2.0	2.0
Thermal Stabilizer, lb	0	0	10	10	0	0	10	10
Aphron Generator, lb	0	1.0	0	1.0	0	1.0	0	1.0
Brookfield Rheology, cp: Initial (Average of Duplicate Evaluations)								
0.5 rpm	6,480	5,840	10,920	10,080	14,360	15,120	23,840	25,080
100 rpm	104	144	239	217	257	220	367	385
Thixotropic Index (TI)	62	41	46	46	56	69	65	65
Fann Rheology								
Plastic Viscosity, cp	5.5	5	8.5	8.5	6.5	7	11.5	13
Yield Point, lb/100 sq.ft.	11.5	12	16.5	16.5	16	15.5	23.5	21.5
3 rpm	8	8	9	8.5	12.5	13	14	14.5
Brookfield Rheology, cp: After Aphron Generation (Average of Duplicate Evaluations)								
0.5 rpm	6,120	22,360	10,480	15,800	15,300	17,320	22,280	29,200
100 rpm	-	-	182	505	290	327	355	620
Thixotropic Index (TI)	-	-	58	31	53	53	63	47
Fann Rheology								
Plastic Viscosity, cp	5.5	14.5	11.5	26	9.5	14	12	20.5
Yield Point, lb/100 sq.ft.	12	35	13.5	28	15.5	15.5	22.5	37
3 rpm	8	11.5	9.5	12	12.5	14	14	19
Brookfield Rheology, cp: After setting 16 hr @ 72°F								
0.5 rpm	6,000	5,520	11,200	10,800	12,880	17,920	15,840	22,800
100 rpm	133	170	167	194	213	278	300	320
Thixotropic Index (TI)	45	32	67	56	60	64	53	71
Fann Rheology								
Plastic Viscosity, cp	4	5	6	7	7	9	7	8
Yield Point, lb/100 sq.ft.	13	12	18	16	15	16	23	23
3 rpm	11	8	11	12	15	16	16	18
API Fluid Loss, ml/30 min, 100 psi (Average of Duplicate Evaluations)								
Spurt Loss, ml/30 min	46	34	0	0	79	44.5	0	0
API Fluid Loss, ml/30 min	81.5	59	11.7	9.5	119.5	78	9	8.5

Table 4

Effect of Thermal Stabilizer on Aphron-Based Fluid

Fluid No.	1	2	3
Composition			
Fresh Water, bbl	1	1	1
LSRV Viscosifier, lb	1.5	1.5	1.5
Aphron Generator, %	0.27	0.27	0.27
Thermal Stabilizer-1, lb	0	0	10
Thermal Stabilizer-2, lb		2	2
Brookfield Rheology, cp: Initial			
0.5 rpm	17,800	13,,800	22400
100 rpm	209	204	292
Thixotropic Index (TI)	85	68	77
Brookfield Rheology, cp: After Static Aging 16 hr @ 180°F			
0.5 rpm	800	4,400	21,000
100 rpm	108	152	257
Thixotropic Index (TI)	7.4	29	82
Brookfield Rheology, cp: After Aphron Generation			
0.5 rpm	4,880	9,200	20,320
100 rpm	384	354	380
Thixotropic Index (TI)	13	26	53
Brookfield Rheology, cp: After Aphron Generation and Setting Static for 20 hr @ 72°F: Decant Large Bubbles			
0.5 rpm	880	4,560	18,800
100 rpm	111	152	260
Thixotropic Index (TI)	7.9	30	72

Table 5

Effect of Thermal Stabilizer I on Rheology and Fluid Loss of HYSST Fluids

Fluid No.	1	2	3
Composition			
Water (fresh), bbl	1	1	1
HYSST XP (97-189), lb/bbl	5	5	5
Thermal Stabilizer I, lb/bbl	0	5	10
Brookfield Rheology, cp:Initial			
Spindle No.	4	4	4
0.5 rpm	40,000	60,000	70,000
100 rpm	620	720	600
Thixotropic Index (TI)	65	83	117
Fann Rheology			
600 rpm	84	96	88
300 rpm	65	76	70
200 rpm	55	67	61
100 rpm	44	52	48
6 rpm	19	28	27
3 rpm	15	20	17
Plastic Vis cosity, cp	19	20	18
Yield Point, lb/100 sq.ft.	46	56	52
Notes:			
Hot-Rolled Overnight @ 180°F			
0.5 rpm	22,000	24,000	52,000
100 rpm	350	300	370
Thixotropic Index	63	80	141
Fann Rheology			
600 rpm	41	48	61
300 rpm	28	37	43
200 rpm	23	33	37
100 rpm	181	26	31
6 rpm	11	14	18
Plastic Viscosity, cp	13	11	18
Yield Point, lb/100 sq.ft.	15	26	25
pH	9.4	9.3	9.3
API Fluid Loss, ml	23	17	14

Table 6

Comparison of Aphron Based System in Fresh Water and Field Water

Fluid No.	1	2
Composition		
Fresh Water, bbl	1.0	
North Dakota Brine, bbl		1.0
LSRV Viscosifier, lb	3.0	3.0
Aphron Generator, lb	1.0	1.0
Fann Rheology		
600 rpm	23	29
300 rpm	18	22
200 rpm	16	19
100 rpm	13	15
6 rpm	7	7
3 rpm	6	5
Brookfield Rheology, cp		
0.5 rpm	7200	7600
100 rpm	152	166
Density, lb/gal		
Initial	8.2	9.2
Handshake, 1 minute	6.7	7.2
Handshake, 1 minute	6.1	6.8
Handshake, 1 minute	<6.0	<6.0

Note: Could not measure below 6.0 on regular mud balance.

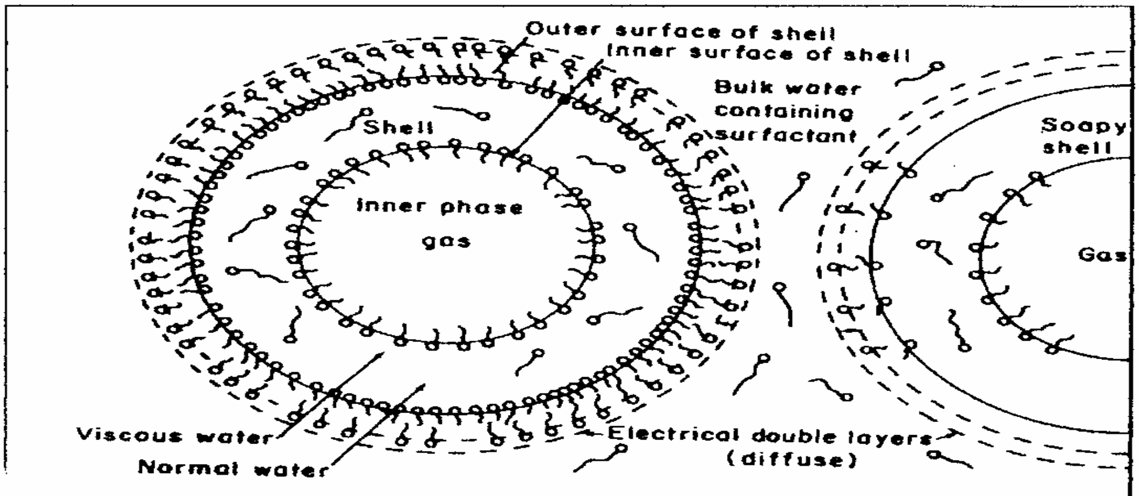
Table 7

Effect of Aphrons on Low Shear Rate Viscosity

Handshake, No. Times	0	10	5	25	30	50
Brookfield Rheology, cp						
0.5 rpm	10,800	5,200	6,000	8,400	12,000	12,800
100 rpm	230	202	184	190	228	224
Brookfield Rheology, cp (After Static Aging for 16 hr @ 72°F)						
0.5 rpm	3,200	11,200	12,400	12,400	12,400	12,400
100 rpm	232	254	248	242	228	220

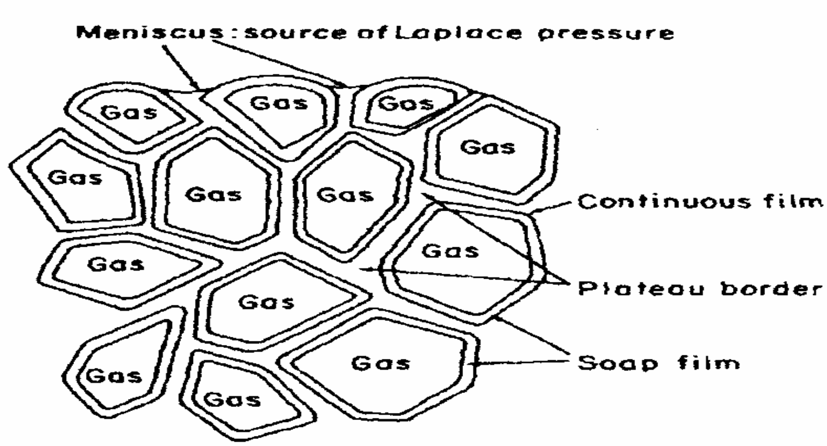
Notes: Sample prepared with 1.5 lb/bb LSRV viscosifier and 1.0 lb/bbl Aphron Generator in fresh water. Sample was sequentially handshaken number of times noted and viscosity taken immediately after shaking. The sample was static aged and the procedures repeated.

Figure 1
Structure of Gas Aphron



After Sebba, 1997

Figure 2
Structure of Gas Aphrons



After Sebba, 1987

Figure 3

Interface Between Shell Film and Continuous Film (Bimolecular Layer)

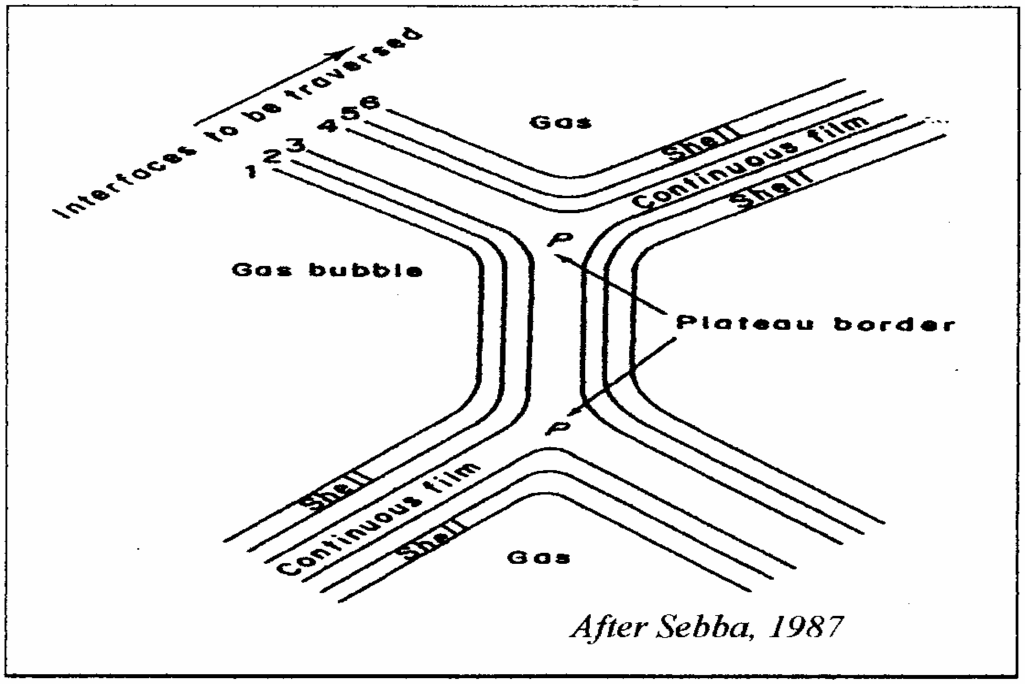


Figure 4

Three Gas Aphron Bubbles: Triangular Plateau Border Area

After Sebba, 1987