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Aphron-based Drilling Fluid: Novel Technology for Drilling Depleted Formations in the North Sea

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Abstract

Drilling depleted reservoirs is fraught with a host of technical and economic problems that often make it unprofitable to further develop some mature fields. Most of the problems center around uncontrollable losses and differential sticking. Frequently, less expensive drilling fluids will be used in a particular interval, even though it may have the propensity to damage the formation. The reasoning holds that such fluids will offset the high costs of losing more expensive muds to the formation. If operators turn to underbalanced drilling as an alternative, the extra time and equipment required for a safe operation can seriously degrade project economics in some applications.

A specialized invasion-control drilling fluid has been developed to drill reservoirs prone to lost circulation. This fluid combines certain surfactants and polymers to create a system of micro-bubbles or aphrons that are encapsulated in a uniquely viscosified system.

Aphron based systems are engineered drilling fluids that aid in well construction by controlling losses in depleted, high-permeability sands while stabilizing pressured shales or other formations. One of the more attractive features of an aphron-based system is that it does not require any of the extra equipment used in air or foam drilling. There are no compressors, high-pressure hoses or connections to add costs and safety concerns. The system uses conventional fluid-mixing equipment to form tough, flexible micro-bubbles.

This paper describes the development and application of the specialized micro-bubbles-based drilling fluid for controlling downhole mud loss in a depleted reservoir in the North Sea. The key issues of this project were excessive overbalance drilling conditions (> 5,000 psi) leading to the risk of highly expensive lost circulation and open perforations in the upper producer, requiring temporary sealing during drilling. The well was successfully drilled to TD without any drilling fluid losses. The authors will detail the laboratory methods used to generate appropriate formulations, the operational procedures, and field application.

Introduction

The drilling problems associated with the depleted reservoirs intrinsic to many of the mature fields throughout the world often make further development uneconomical. The water-wet sands that typify many of these zones propagate seepage losses and differential sticking, both of which are extremely expensive to correct. Uncontrollable drilling fluid losses frequently are 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 pressured sequences with a single drilling fluid. Drilling such zones safely and inexpensively is very difficult with conventional rig equipment. Such problems have led some operators to forgo continued development of these promising, yet problematic, reservoirs.[1]

Excessive overbalance pressure generated when using conventional drilling fluids is thought to be the primary cause of lost circulation and differential sticking when drilling these wells. The equipment required to manage aerated muds or drill underbalanced is often prohibitively expensive, and meeting safety requirements can be an exhaustive effort. Furthermore, these techniques may fail to provide the hydrostatic pressure necessary to safely stabilize normally pressured formations above the reservoir.

Recently, a new drilling fluid technology based on aphrons – uniquely structured micro-bubbles -- was employed to successfully drill a depleted reservoir in the North Sea. The use of aphron-based drilling fluids has proven to be a successful and cost-effective alternative to drilling underbalanced.

Description of Aphron Structure

An aphron comprises two fundamental elements[2]:

- A core that is commonly, but not always, spherical. Typically, the core is liquid or gaseous.

- A thin, aqueous, protective shell with an outer hydrophobic covering. The aqueous shell contains surfactant molecules positioned so that they produce an effective barrier against coalescence with adjacent aphrons.

As illustrated in Fig. 1, the encapsulating shell protects the aphrons, which can attract one another to build up complex aggregates. The encapsulating surfactant film is actually a high-viscosity bi-layer: the inner layer contains surfactants whose hydrophobic ends point into the core and whose hydrophilic ends reside within the shell. The outer layer has surfactants whose hydrophilic ends point into the shell and whose hydrophobic ends lie in the bulk liquid.[2]

In contrast to an aphron, a conventional surfactant-stabilized bubble, as shown in Fig. 2, is simply a sphere of gas separated from its aqueous environment by a thin surfactant film. The hydrophobic tail of the surfactant is oriented towards the gas core, while the hydrophilic head is oriented towards the bulk water.[2] Thus, a conventional bubble (Fig. 2) has a water-wet or hydrophilic outer boundary, while an aphron (Fig. 1) has a hydrophobic boundary.

Aphrons created under ambient conditions – as is the case in the field during the initial incorporation of air into the drilling fluid -- may have a rather broad size distribution. A technique developed recently, the Acoustic Bubble Spectrometer, permits quantitative measurement of the bubble size distribution in opaque fluids.[3] A typical bubble size distribution measured on a highly diluted aphron-based drilling fluid is shown in Fig. 3.

An advantage of aphrons is that they can clump together, creating large aggregates, as illustrated in Fig. 4.

A meniscus is believed to envelop, or wrap, all the aphrons in such a macro-structure, thereby imparting to the aggregate the same liphophilic character possessed by the individual aphrons .[2]

The "meniscus wrapping theory" is literally endorsed by the mechanism known as "Laplace Pressure." This theory simply states that when a flat hydrophobic surface (i.e. plateau border from the aphron structure) dips into a water-wet liquid, a contact angle will exist where the liquid and gas meet[2]. If two such "liphophilic charges" are close together, the effect of the two contact angles will be the generation of curvature, or meniscus, in the liquid surface between those two hydrophobic droplets

Aphron Structure Stability

The aqueous bi-layer in the aphron structure will remain stable as long as the water film meets certain criteria for film thickness and viscosity.[2]

First, the film must have a certain minimum thickness.[4] Anything below this value, such as the stretching that accompanes an increase in the aphron volume, will break the film.

Secondly, the film must have a minimum viscosity. Water molecules tend to diffuse out of the film and into the bulk liquid, as a result of a phenomenon known as the "Marangoni effect".[2,4,5] This also serves to thin and destabilize the film. However, the rate of transfer of film water is inversely proportional to viscosity. Consequently, in designed aphron structures, a viscosifier such as a biopolymer is generally added.

There are other properties that the film must almost certainly possess to have a sustainable aphron structure. One is low diffusivity. When an aqueous fluid containing 15% v/v air under ambient conditions is subjected to a pressure of 150 psi, compression alone will reduce the air volume 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. all of the air could dissolve in water at 150 psia. This is not observed for aphron-based fluids. Indeed, not only do aphrons survive above 200 psia, they also do not achieve the small size expected from compression. It is thought that the aphron film is strong and impermeable enough to resists compression and suppresses the transport of air to the aqueous environment.

Generally, diffusion or the transport of air through the film is considered a rapid process for conventional bubbles.[6] Even for polymeric surfactant-stabilized bubbles, diffusion is expected to occur on the order of seconds. The experiments by Bredwell and Worden[6] also showed that while stabilization of bubbles with surfactants can reduce water-air mass transfer coefficients by factors of two to three, reduction of bubble size by the surfactants leads to a vast increase in interfacial area and a net overall increase in water-air transfer. Aphron films appear to be much less permeable. Indeed, experiments conducted in a visualization cell indicate that they can survive up to at least 1500 psi for extended periods of time. PVT experiments suggest a significant lag time also occurs during depressurization.[1]

Aphron Bridging Mechanism

The vast majority of reservoir formations are water-wet. Capillary pressure resists intrusion of a hydrophobic micro-bubble into a water-wet capillary restriction in the formation. An insular globule of non-wetting fluid moves only by virtue of the differential pressure applied across it within a moving wetting fluid.[7,8] Before a globule can be displaced, this pressure differential must be sufficient to overcome the capillary pressure. Although the pressure differential may be very small for a single bubble, Jamin showed that the cumulative resistance of many bubbles in a capillary restriction might be large. [7,8]

It is highly unlikely that pressure gradients of sufficient magnitude could be applied in the field to overcome this "Jamin Effect" and force deep penetration of aphrons into the interconnected microfracture/pore network in permeable formations.[8]

Operational Challenges

A well in the Dutch sector of the North Sea was planned to be deepened near vertically from the main reservoir through the intermediate claystone into the lower reservoir. The well plan called for TD at 10,508 ft, which was approximately 56 ft above the base of the main resservoir. The main reservoir was depleted to 794 psi, whereas the lower reservoir was expected to contain a reservoir pressure of 3,689 psi. At the same time, the intermediate claystone was expected to have sand stringers that might still be at virgin pressure of 5,380 psi.

The formation strength of the main reservoir formation was perceived as the main project risk since this might have been decreased substantially due to the high depletion. The risk of fracturing the main reservoir was compounded greatly by the fact that the intermediate shale needed to be drilled with a relatively high mud weight to maintain pressure control within the sand stringers and to aid stability. A minimum static mud weight of 9.66 lb/gal was required to balance the maximum pore pressure in the intermediate claystone. Modelling using proprietary hydraulics software indicated that during drilling the maximum ECD's would be in the region of 10.8 – 11.24 lb/gal. Therefore, in order for the well to be deepened, the main reservoir formation had to withstand these pressures.

These were the main reasons justifying use of the micro-bubble technology for drilling this interval. The risk analysis indicated the pore pressure criteria and the target formation type favour the use of the aphron technology. However, because of the high annular pressure (5,278 psi) the drilling fluid system has to be designed with 25 – 30 sized $CaCO_3$.

The main concern at the start of the deepening phase was closing/sealing the existing perforations. This should prevent the cross flow between the deeper, pressured reservoir and the current, depleted reservoir. In addition, this would protect the existing productive formation from downhole losses, further fracturing, and formation damage.

Bridging Material Optimization and Perforations Sealing

The bridging material simulation was carried out using the maximum permeability (10 mD) and D_{90} ideal packing theory (IPT). Ideal packing can be defined as the full range of particle size distribution required to effectively seal all voids, including those created by bridging agents. The IPT advocates using the largest particle sizes equal to the size of the fracture to be plugged. The rule is having D_{90} equal to fractures openings size.

The IPT differs from the traditional bridging concept – Abrams' rule. The Abrams' rule states: "the median particle size of the bridging material should be equal to or slightly greater than 1/3 the median pore size of the formation." It goes on to state that the concentration of the bridging particle size solids must be at least 5% by volume of the solids in the fluid. Essentially, Abrams' rule only indicates that plugging has begun and does not address an ideal packing sequence for optimum sealing. The analyzed bridging materials were the standard $CaCO_3$ varieties. Figure 5 presents the optimum calcium carbonate blend based on the particle size distribution. The recommended bridging material blend to be mixed in the whole system was very fine $CaCO_3$ (17.5 ppb) and fine $CaCO_3$ (7.5 ppb). As mentioned before, one of the concerns at the start of the deepening phase was closing/sealing of the existing perforations. The perforated interval was approximate 325 ft. The perforations were performed with 2 ¾-in guns with 6 perforations/meter and 60° deflection. The ideal perforation geometry was calculated to be 0.27 in diameter and 16.5 in penetration. An estimated 1782 perforations in the target interval was considered. The total volume of perforations (considering ideal geometry) was then calculated 0.1736 bbl.

The perforations bridging was executed by spotting 50 bbl aphron-base pill formulated with 75 ppb sized $CaCO_3$ across the perforated zone. This pill was mixed on the rig in the slug pit by adding an additional 50 ppb of combined medium $CaCO_3$ (25 ppb) and coarse $CaCO_3$ (25 ppb) over the mud received from the mud plant (treated already with 25 ppb of fine and very fine $CaCO_3$).

The recommended volume (50 bbl) carried 0.76 bbl equivalent volume of sized $CaCO_3$ enough for filling the perforations plus 350 % excess.

Well Control Procedures when Drilling with Aphron-based Drilling Fluid

Standard industry kick control calculations and procedures are to be employed when managing a well control situation. Gas is usually circulated out as a gas bubble. However, due to the surfactant composition of the aphron-based drilling fluid, it was expected that, when circulated through a choke, the resultant pressure drop would create additional aphrons. This was tested in a simulation well (yard test) and, when the aphron mud was circulated through the choke, a fast developing foamed, fluffy, hyper-aphronized structure was created in contact with atmospheric pressure. This situation is normal for an aphron-base mud and for the field operation the following procedure was suggested.

1. The "gas-laden fluid" that is passed through the choke should be placed into a separate holding tank to reduce the low-shear-rate viscosity (LSRV) and treatment with an alcohol-based defoamer.
    a. 0.25 – 0.75 ppb alcohol based defoamer
    b. 15% fresh water (for LSRV reduction – optional)
2. The fluid should then be passed through a vacuum degasser (optional) to remove the entrained gas.
3. Before adding the fluid back into the active system, the aphronizer surfactant concentration and LSRV should be reestablished.

Pressure/Fluid Density Variation with Depth as a function of Aphrons Concentration

To explain and calculate aphron concentration and size with increased pressure and overall pressure difference, several simulations and models were used. The aphron compression with pressure was simulated using sigmoid curves with complete depletion of aphron structures at 3,000 psi. The wellbore and the target interval (surface to bottom) were divided in 500-ft subintervals. The temperature was modeled using a linear profile from surface to bottom. For each 500-ft interval the Boyle's law was applied (temperature, volume and pressure in the form of $(P_1V_1)/T_1=(P_2V_2)/T_2$ using the upper interval as input for the one below all the way down to TD. The Boyle's equation provided the aphron percentage and the interval-by-interval pressure calculation was done with the corrected density (Fig. 6). After that the comparison was made (ΔP) between the equivalent static density (ESD) of an aphron-based system and the ESD of an aphron-free system. The calculated pressure difference was not higher than 50 psi, with the aphron concentration of 15% at surface (Fig. 7). This confirmed that the hydraulics models (bubbles-free, high LSRV fluids) could be used with no problems for the aphron-based system.

Another simulation was the aphron size change with pressure. This calculation was done using two assumptions: 100 microns the average aphron size at surface and constant population throughout the pressure increase stages until the collapse pressure is reached (Fig. 8). The conclusion of this simulation was that, although the increased pressure reduces the total aphrons volume very quickly (the volume occupied by the aphron structures in the whole system), the overall size decreases much slower (from 100 microns to 22 microns). This is a direct response to the power three relation between volume and radius of spherical structures. This demonstrates that the aphrons are able to keep their size for optimum bridging while the overall pressure reduction is marginal.

Operational Summary

As mentioned before, the first phase of the project was sealing the existing perforations. This was successfully performed with one 50-bbl aphron-based pill formulated with 75 lb/bbl sized $CaCO_3$. Upon completion of displacing the well to aphron-based drilling fluid, a pressure limit test of 58 bar surface pressure (11.25 lb/gal equivalent mud weight) was successfully conducted.

The milling operation was successfully completed utilizing the aphron-based drilling fluid without any problems (e.g. lost circulation). The milling assembly was pulled out of the hole (wet), and then the drilling assembly was made up and ran into the hole.

Drilling proceeded to 11,522 ft where the decision was made to pull the bit due to an abysmal rate of penetration. After tripping the string form the hole a new motor was picked up and the same bit was tripped to bottom. The hole was then drilled to a final depth of 11,650 ft measured depth (MD) without any mud losses.

After reaching the target depth, the 2 7/8-in. slotted liner was picked up and ran into the hole. The liner was set at 11,650 ft without any incidents or drilling fluid losses.

Lessons Learned and Conclusions

During the first phase of the aphron-based mud fill-in/displacement procedure (the first 189 bbl), an in-line pressurized flow meter was used. This provided an accurate measurement with no volume errors related to the aphron compression. However, if the pumping had been done based on the relative pit volume changes, the volume calculations would have been changed (increased) with 10% (aphron concentration). This is due the aphron shrinkage effect with pressure.

Two complete hole displacements were made on this well, both times inside casing with a known volume to displace. Both times, the quantitative displacement was more than the calculated pump stroke displacement. On the two displacements, the % volume shortfall was practically equivalent to the % aphrons.

Another observation that lends credence to the above-described theory is the relationship between the pump strokes and flow meter while drilling. The difference between the calculated flow rate (based on the pump strokes) and the flow meter readings were very close to the actual air content of the drilling fluid.

Because of the high ECDs on these types of wells, it is vital to establish the maximum allowable flow rates for efficient drilling. With this in mind, a rule of thumb for establishing the true flow rate could be that the % pump output efficiency be reduced by the % aphrons.

The objective to extend the borehole to a new potential pay zone without compromising the existing production from the substantially depleted reservoir has been successfully accomplished without any mud losses or any fracturing or drilling fluid related problems.

Acknowledgments

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SI Metric Conversion Factors

bbl	X 1.5897	E-01	= m^3
°F	X (°F-32) X 5/9 = °C		
ft	X 3.048	E-01	= meters
gal	X 3.785	E-03	= m^3
in	X 2.540	E-02	= meters
lb	X 4.536	E-01	= kg
ppb	X 2.853	E+00	= kg/m^3
ppg	X 1.198	E+02	= kg/m^3
ppg	X 1.198	E-01	= Specific Gravity (SG)

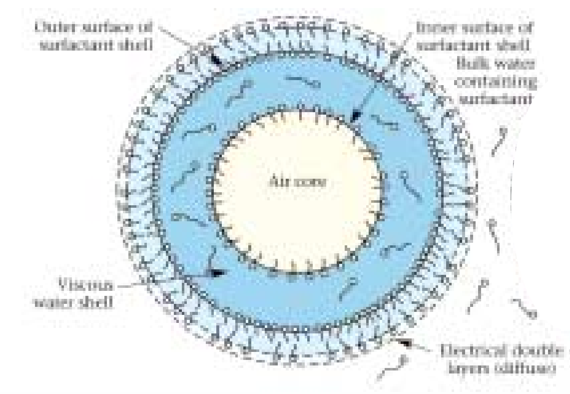

Fig. 1 – Structure of colloidal gas aphron[2]

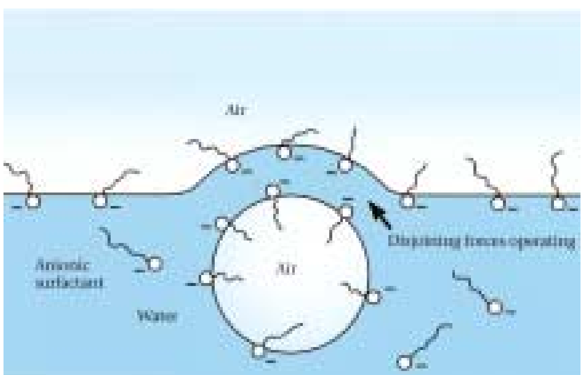

Fig. 2 – Structure of a conventional surfactant-stabilized bubble[2]

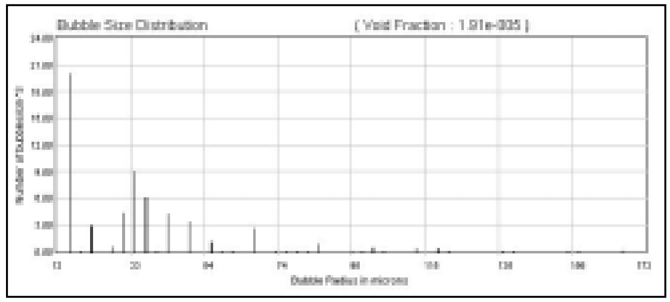

Fig. 3 – Bubble Size Distribution in a diluted aphron-based drilling fluid, as measured with the Acoustic Bubble Spectrometer

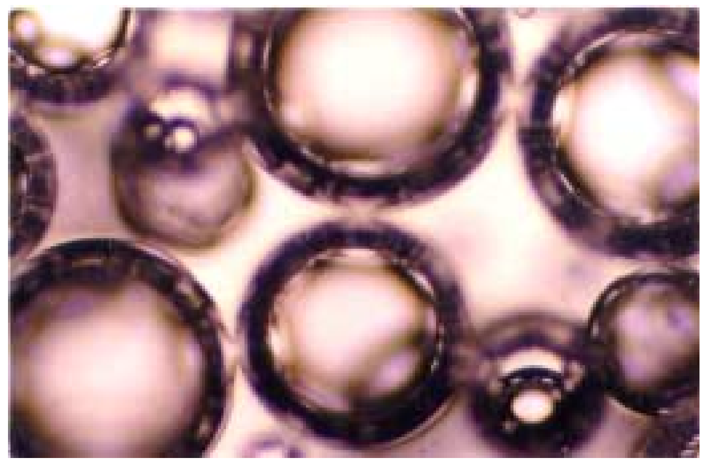

Fig. 4 – Gas-core aphrons can clump together, creating large aggregates, and these macro-structures behave in a similar manner as an individual aphron.

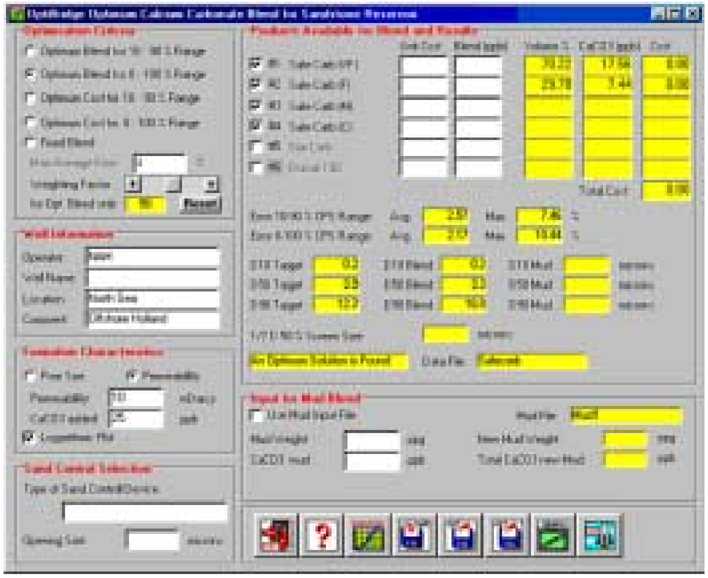

Fig. 5 – The optimum calcium carbonate blend based on the particle size distribution.

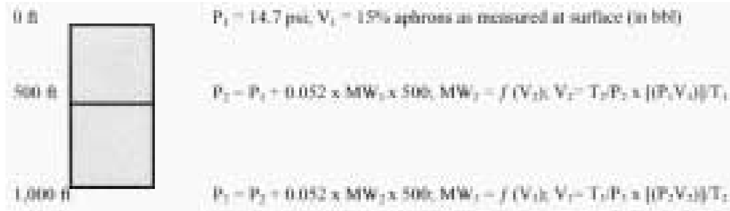

Fig. 6 – The Boyle's equation applied for 500-ft intervals to determine the aphron percentage, the interval-by-interval pressure and the corrected density.

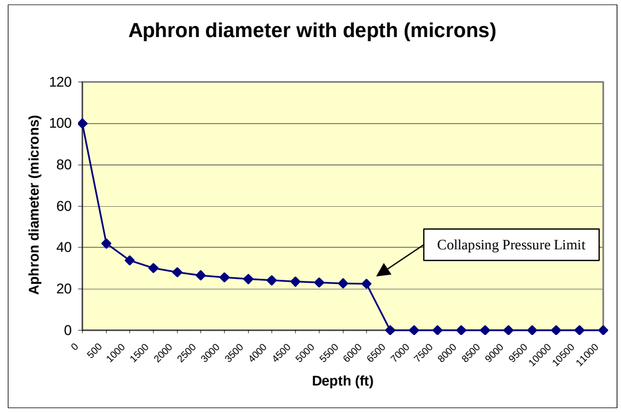

Fig. 8 – Aphron size change with pressure

					Wellbore volume (bbl)			214
			Aphron-free		Aphron concentration (%)			15
	Aphron system ESD		mud ESD					
Depth (ft)	bar	psi	psi	% aphron	delta P (psi)	Temp (deg F)	Density (ppg)	Aphron Vol. (bbl)
0	1.00	14.70	14.70	15.0000		70	8.2110	32.1
500	15.52	228.19	265.86	1.0647	37.67	77.1	9.5571	2.278539583
1000	32.43	476.67	517.02	0.5568	40.35	84.3	9.6062	1.191578067
1500	49.42	726.43	768.18	0.3963	41.75	91.4	9.6217	0.848051002
2000	66.44	976.60	1019.34	0.3178	42.74	98.5	9.6293	0.680027331
2500	83.47	1226.96	1270.50	0.2712	43.54	105.6	9.6338	0.580438017
3000	100.51	1477.44	1521.66	0.2404	44.22	112.8	9.6368	0.514562816
3500	117.55	1727.99	1772.82	0.2186	44.83	119.9	9.6389	0.467765213
4000	134.60	1978.61	2023.98	0.2022	45.37	127.0	9.6405	0.432808134
4500	151.65	2229.26	2275.14	0.1896	45.88	134.2	9.6417	0.405703414
5000	168.70	2479.94	2526.30	0.1795	46.36	141.3	9.6427	0.384072881
5500	185.76	2730.65	2777.46	0.1712	46.81	148.4	9.6435	0.366410504
6000	202.82	2981.38	3028.62	0.1644	47.24	155.6	9.6441	0.35171622
6500	219.87	3232.13	3279.78	0.0000	47.65	162.7	9.6600	0
7000	236.96	3483.29	3530.94	0.0000	47.65	169.8	9.6600	0
7500	254.04	3734.45	3782.10	0.0000	47.65	176.9	9.6600	0
8000	271.13	3985.61	4033.26	0.0000	47.65	184.1	9.6600	0
8500	288.22	4236.77	4284.42	0.0000	47.65	191.2	9.6600	0
9000	305.30	4487.93	4535.58	0.0000	47.65	198.3	9.6600	0
9500	322.39	4739.09	4786.74	0.0000	47.65	205.5	9.6600	0
10000	339.47	4990.25	5037.90	0.0000	47.65	212.6	9.6600	0
10500	356.56	5241.41	5289.06	0.0000	47.65	219.7	9.6600	0
11000	373.64	5492.57	5540.22	0.0000	47.65	226.9	9.6600	0
end								
	Aphron mud		Aphron-free mud				Aphron mud	

Density (ppg)	9.66
Temp (deg F; surface)	70
Temp (deg F; bottom)	224
TVD (ft)	10800

Aphron volume (surface)	32.1 bbl	5.1039 m3

Aphron diameter

depth (ft)	diameter (micron)
0	100
500	41.82
1000	33.70
1500	30.10
2000	27.96
2500	26.53
3000	25.48
3500	24.69
4000	24.06
4500	23.54
5000	23.12
5500	22.76
6000	22.45
6500	0.00
7000	0.00
7500	0.00
8000	0.00
8500	0.00
9000	0.00
9500	0.00
10000	0.00
10500	0.00
11000	0.00
end	

Aphron population	9.75268E+12

Color code: input values; calculated values

Note: The Aphron population calculation was done assuming 100 microns average size at surface conditions and no population changes until the aphron reach 20 microns diameter and start implosion process

Fig. 7 – The comparison (ΔP) between the equivalent static density (ESD) of an Aphron-based system and the ESD of an Aphron-free system. The calculated pressure difference was not higher than 50 psi, with the aphron concentration of 15% at surface