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Resolving Losses and Increasing the Drilling Window in Depleted Zones by Constantly Strengthening Wellbores

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Abstract

The issues of drilling through depleted zones, especially in mature areas, are increasing in importance as they are a frequent and familiar scenario for many fields. Pressure overbalances have been reported as high as 13,000 psi, but are more typically range from hundreds to thousands of psi. Wellbore stability problems associated with these zones can be linked to both drilling-induced and pre-existing fractures, resulting in fluid losses. It is generally acknowledged that the solution to these problems is a combination of drilling fluid optimization and proper drilling practices. The current fluid solution incorporates the use of large particulates in the form of a pill to seal the fractures and consequently increase the drilling window. While their advantages are known, large particulates also carry disadvantages such as the retroactive nature of being a remedy, rather than a prevention, and the non-productive time associated with this technique.

The service company and the oil company conducted extensive development to change the popular approach applied for wellbore-strengthening solutions. The resulting methodology to strengthening is based on the beneficial manipulation of fracture propagation pressure and continuous application of specialized wellbore-strengthening additives, thus making the drilling fluid itself create a virtual liner against the wellbore. The authors will present selected laboratory test methods and results, including a large scale fracture test and the associated mathematical modeling. This work shows a potential improvement in the drilling window while meeting environmental regulatory requirements in the Gulf of Mexico.

Introduction

When drilling through depleted pore pressure sandstone formations in the Gulf of Mexico, and in other areas around the globe, operators often encounter drilling fluid losses. This is due to the pressures exerted on the formation by the column of drilling fluid exceeding the pore pressure of the formation. So much overburden is present that fractures can be induced leading to whole drilling mud lost to the formation in addition to what can be lost due to naturally occurring fractures or vugular zones.

The traditional solution has been the application of particulate lost circulation materials or LCM. The general concept being that adding solids with an appropriate size distribution for the size of the fracture widths encountered or induced downhole, will allow the weighting solids in the drilling fluid to then bridge over the fracture mouths and form the filtercake on the wellbore as designed. The pressure which drives the LCM into the fracture mouths will equilibrate at some point, allowing the solids to then take on the task of supporting the hoop stress in the formation just outside the wellbore, a technique commonly referred to in industry as "stress caging". These LCM come in many different size distributions, shapes, orientations, and material types. Yet, they all still have on commonality. The application of the LCM solution is performed after the confirmation of fluid losses. This could be a substantial time delay depending on the depth of the well. Even still, particulate solutions are not without risk to the production zone due to issues such as fine solids migration. In extreme situations, a pump-able and/or curable pill might have to be placed downhole, held, and then drilled through.

The mechanism of inducing fractures has been investigated, modeled, and presented to the oil and gas industry. This model presented by Bernt Aadnoy, et al in SPE 105499 however, does not fully take into account the interaction of the formation rock and the deposited filtercake. Not only is the model deficient in predicting the true fracturing pressure when a traditional filtercake has been deposited, it does not allow for any mechanical or chemical enhancements which could be made to the filtercake.

There is a clear need in the industry for a novel approach to drilling through depleted zones. The target of the project was initially to develop a synthetic invert emulsion fluid system which could continuously strengthen the wellbore by effectively increasing the drilling window. Or in other words, to lay down an enhanced filtercake, one capable of essentially increasing the fracturing pressure. What was developed over the many subsequent months, was a blend of synthetic based drilling fluid additives which enhances the filtercake which is being deposited as the well is drilled. With use of the developed solution, the pressure at which fractures propagate via whole drilling mud invasion could be increased, the wellbore would be continuously strengthened without the addition of large particulates or traditional LCM, and the safe drilling window could be increased. The novel technology developed collaboratively by the service company and the oil company also has the potential to drastically reduce non-productive time associated with lost circulation in depleted zones.

Development

As the development of the system and additive package began, the need for the potential solution to act near instantaneously was identified early. This meant that a filtercake with enhanced properties would be an ideal technique. The smart filtercake developed via the additive package would then need to be deposited rapidly on the wellbore surface, be stronger than traditional synthetic-based drilling fluid filtecakes, as well as more resilient if the event of fracturing behind the filtercake-wellbore surface complex. In order to achieve this property, the whole mud must de-fluidize rapidly and then seal off the formation from filtrate invasion. This phenomena could also be thought of as a high initial spurt loss relative to the flattening off or complete shut off of the flow of filtrate invading the formation. Different 14.0 pound per gallon candidate fluids where initially screened for this characteristic in a range finding exercise for additive concentration as compared to a baseline (base), formulated as a simplified synthetic based fluid at 14.0 pounds per gallon.

Screening

During this initial range finding screening process, new or clean lab drilling fluids were formulated and aged in roller ovens at 150 °F. A sampling of some of the various formulations explored is presented in the next section. Attention was of course payed to the impact on rheology, however, that was not our primary screening tool. A standard permeability plugging tester (or PPT) was employed. During the test a differential pressure of 2500 psig is applied to the sample which is heated to 250 °F and it is allowed to deposit a static filtercake on a media disk while the filtrate collection is monitored. Volumes are collected and recorded to observe the initial spurt loss as well as the total amount of filtrate collected over the hour. Traditionally the tests are performed through an aloxite, or other ceramic, disk of varying permeability depending on the experimenter's requirements. Initially we employed this method with 40 micometer or micron disks but quickly evolved to disks cut from actual sandstone formations of varying (low, medium, and high) permeability for greater representation of field behavior. The below Figure 1 shows this spurt loss and shut off behavior of the enhanced package and filtercake.

Figure 1 - Fluid loss results by PPT

Formulation

The baseline formulation amounted to a synthetic based drilling fluid system with some additives responsible for tasks such as boosting and flattening rheology removed. The primary screening metric as stated was the unique fluid loss property and subsequently the enhancement to the filtercake properties. As the density range of interest was approximately 12.0 to 16.0 pounds per gallon, most formulations were prepared to be 14.0 pounds per gallon with synthetic water ratios of between 75/25 and 80/20. Upon adding some components, the aqueous phase would increase. In the interest of leaving the rest of the formulation the same as the baseline, to truly observe the effects of the strengthening additives, adjustments to synthetic water ratio were not made.

The below Table 1 presents four different formulations as examples along with the formulation densities and synthetic water ratios (SWR). Additionally presented are the rheological profiles in Table 2.

Table 1 - Baseline and developed formulations

	Formulation			
Product:	Base	A	B	C
IO 16-18, g	146	132	132	132
Organoclay, g	3	3	2	3
Lime, g	4	4	4	4
Emulsifier, g	7	7	7	7
Wetting Agent, g	2	2	2	2
25% CaCl2 Brine, g	82			
37.6% CaCl2 Brine, g		30	30	30
WATER, g		5	5	5
Barite, g	350	350	350	350
Enhanced WS Package 1		57		
Enhanced WS Package 2			62	53

Mud Wt, ppg	14.1	14.3	14.3	14.5
O/W ratio	75.3%	79.7%	79.7%	80.7%

Table 2 - Baseline and developed formulation rheologies

	Formulation			
	Base	A	B	C
Mud Appearance	AHR	AHR	AHR	AHR
RHEOLOGY	150°F	150°F	150°F	150°F
600 RPM	48	112	133	170
300 RPM	28	64	76	100
200 RPM	21	47	57	75
100 RPM	14	29	35	48
6 RPM	6	7	9	13
3 RPM	5	5	7	10
GELS 10"	6	6	8	12
GELS 10'	7	8	11	13
APPARENT VISC. (cP)	24	56	66.5	85
PLASTIC VISC. (cP)	20	48	57	70
YIELD POINT ($lb_f/100\ ft^2$)	8	16	19	30

To further demonstrate that the enhanced wellbore strengthening package does not utilize large particles, Figure 2 shows the particle size distribution of the baseline and the formulation which was yard tested (further described in the section "Large Block Sandstone Fracturing").

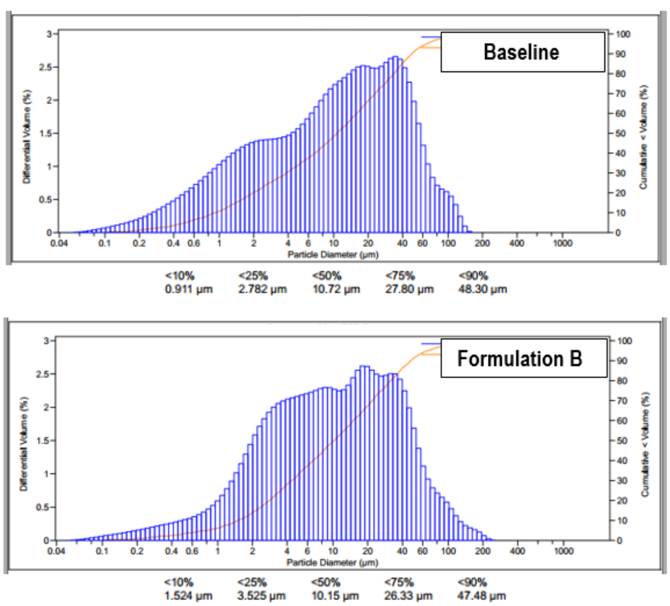

Figure 2 - Particle size distributions

Fracturing of Formations

In addition to the formulation screening, experimentation was also done on fracturing of various sandstone cores of differing geometries. The fracture experiments were done on custom equipment with the initial goal of proof of concept. Unweighted formulations of the baseline and an early version of the enhanced wellbore strengthening package were tested to determine it the fracture propagation and breakdown pressures could indeed be raised. These equipment are capable of simulating overburden stress as well as the maximum and minimum horizontal confining stresses on rectangular geometry, or in the cylindrical geometry a horizontal confining stress. In these experiments, run at ambient temperature, the sample was prepared, and injected into a pre-saturated core. In all instances cores were saturated but no pore pressure was applied. Saturation was typically done with water for convenience. With the core sample under simulated downhole pressures, the candidate formulation would then be pumped into the core wellbore at a constant flow rate while the pressure, including wellbore pressure, would be monitored by data acquisition system. In the proof of concept experiments, the sample with the enhanced wellbore strengthening package fractured at a higher pressure, thus the breakdown pressure was raised significantly. The fracture initiation pressure, as calculated from the inflection of the derivative of the wellbore pressure, had remained similar to the baseline. Therefore the enhanced additive package had indeed strengthened the wellbore without the use of traditional particulate LCM.

Simulating Growing Fracture Mouth

Another major developmental tool was another custom piece of equipment, the High Pressure Fracture Tester, capable of simulating a fracture of fixed or growing width. A schematic of the equipment is presented in Figure _. Custom aloxite disks of fixed permeability (for continuity) were utilized throughout testing. The candidate formulations were prepared then injected into the test apparatus. Inside, two aloxite disks, one with a wellbore hole, were under pressure to create a closed fracture. Then the sample was injected into the wellbore at constant flowrate while the wellbore, confining, and thus differential pressures were monitored through a data acquisition system. Throughout the experiment, the pressure closing the disks was slowly removed, thus the fracture width or simulated fracture mouth, was slowly opened. Through the use of the equipment's linear vertical position transducer, the width of filtercake failure as measured by the loss of wellbore pressure by transducer was recorded and compared as the enhanced wellbore strengthening package evolved. The more successful enhanced wellbore strengthening packages were able to keep a larger width (measured in microns) sealed as the width grew from a completely closed or zero micron fracture to the width at failure. As the development work continued, successful packages were retested, tested for fluid loss via PPT, and checked for rheological profile.

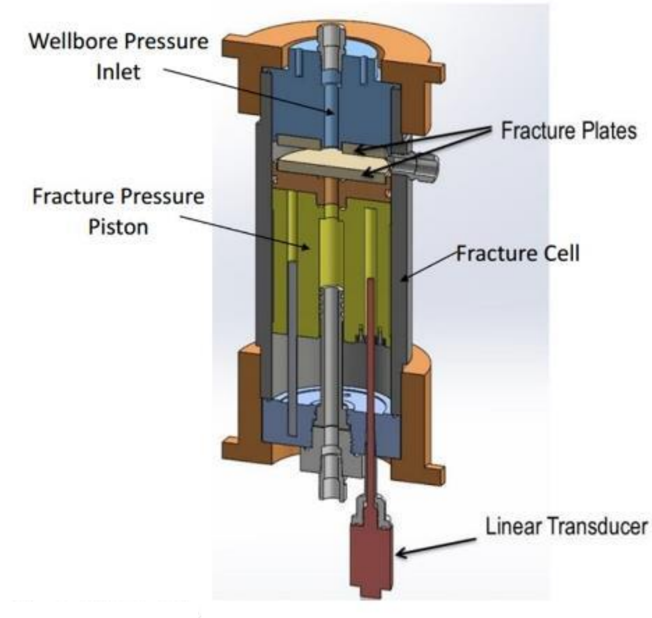

Figure 3 - High Pressure Fracture Tester

Large Block Sandstone Fracturing

The work done on the fracturing did identify a need to move to a larger sample of sandstone. Fortunately M-I SWACO, A Schlumberger Company had access to the capabilities at TerraTek, A Schlumberger Company, to run two tests in the large block stress frame, or a large block fracture tester. The sample used was very close is rock properties as the disks and cores which the majority of the development work was done at the service company. This constituted the best opportunity for a yard test of the technology. The baseline formulation and the baseline with enhanced wellbore strengthening package (formulation B) were formulated in Houston and shipped to the yard test facility, where they were re-homogenized and checked for basic properties such as rheological profile. The sandstone blocks were prepared in a lengthy process which included saturation of the block, inserting and securing a simulated liner in the borehole, and loading the block into the stress frame. The sandstone samples measured 27.25” x 27.25“ x 32” with the simulated wellbore or borehole being 1” in diameter. Once the laborious process or preparing then placing the block in the frame were completed, the installation of the hydraulic jacks and lid of the test chamber occurred. Then the appropriate overburden stress was applied to the sample to emulate downhole pressure conditions. The maximum (σ_{Max}) and minimum (σ_{Min}) horizontal confining stresses were applied in a ratio of 1.5 to 1 in order to ensure a two wing fracture simulating potential stress differences in the field. For each of the two tests performed, fluid was injected at a constant flow rate of 5 mL/min. The results of the yard test are further elaborated on in the Performance section.

Performance

The results from the large block sandstone fracture yard testing performed at TerraTek were quite interesting. Not only was the confirmation of the enhanced wellbore strengthening package by a higher observed breakdown pressure but the modeled fracture mouth as calculated by a Schlumberger Gould Research fracturing model provided by John Cook indicated continuous wellbore strengthening. The strengthening was proven by model calculations of fractures behind the filtercake of larger calculated fracture width and length.

An additional result of the yard test was the observance of the self-healing property. Filtercake failure is thought to begin as a pinhole which upon further failure allows whole mud to invade and thus propagate the fracture. As evident in the figure below, not only did the enhanced wellbore strengthening package increase the breakdown pressure of the sandstone by nearly 600 psig, the larger saw tooth pattern of the pressure vs time curve highlights the ability of the enhanced filtercake to not only re-seal but allow wellbore pressure to build again by 600 to 700 psig. This is expanded upon in the Self-healing Filtercake section.

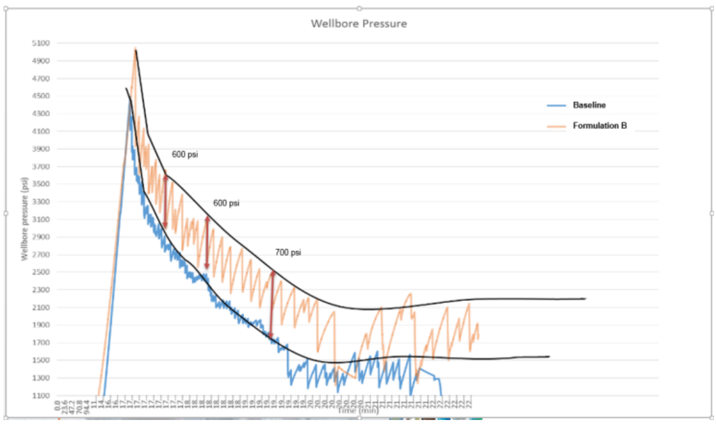

Figure 4 - Yard test results

Additional testing showed there are also formation sealing enhancements as a result as confirmed by formation damage return permeability tests. Not only was there a 6-7% improvement in return permeability, but more importantly the flow initiation pressure was reduced by an order of magnitude form 25 psig to 2 psig.

Strengthening

The following figure shows the two large sandstone fractured blocks that were autopsy cored on the side which was not fractured completely through to the horizontal confining pressure.

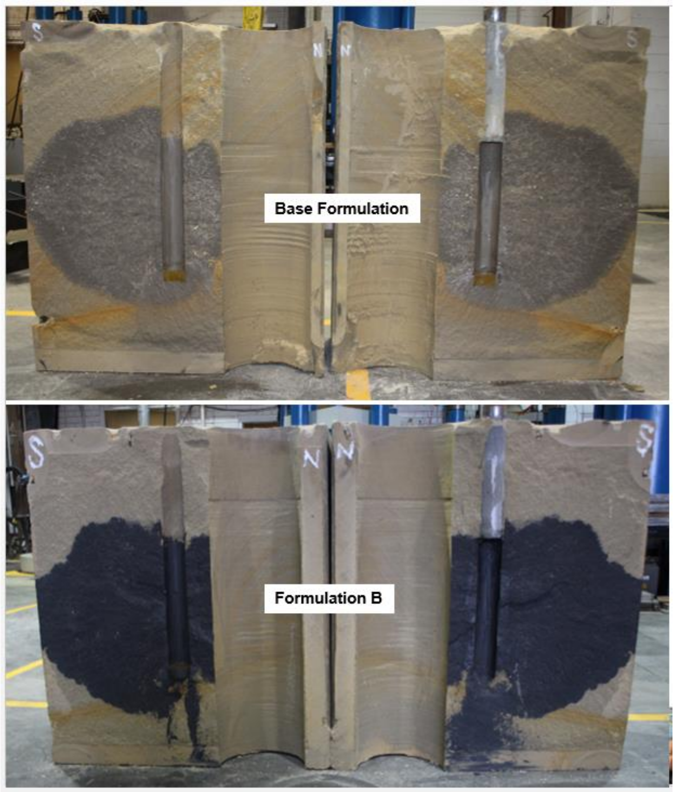

Figure 5 - Large sanstone samples post yard test

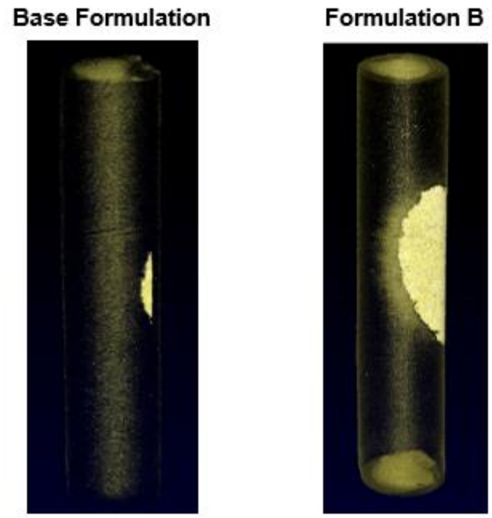

Figure 6 - CT scans of autopsy cores

The wellbore was strengthened by increasing breakdown pressure nearly 600 psig the yard test was successful. The potential exists for the strengthening to be even greater with the benefit of downhole temperatures. By the Cook modeling, the solution could be capable of increasing the drilling window by 0.5 ppb in the depleted zones. A scenario also exists in which this technology is used, and when losses are encountered, simply by lowering the pump rates and thus pressures and ECD, the well section could be continued without having to pull out of hole to pump large particulate LCM into the depleted zone.

Self-healing Filtercake

The following image shows a CT scan of the two autopsy cores from the baseline formulation and formulation B. The ability of the filtercake to self-heal when breached is demonstrated, although the sample fluid was already hydraulically communicating with the horizontal confining pressure, the filtercake re-sealed the wellbore, allowing the opposite fracture wing to propagate. Notice how the core from formulation B has propagated further through the sandstone samples.

Future Work

The future development work will include continuing the work on treating field muds with the enhanced package. Although work has begun on treating field synthetic field drilling fluids, it has yet to be optimized. The wealth of the development was done on clean laboratory built samples.

Temperature effects will also be heavily investigated. The results of the yard test validated the proof of concept however, the experimentation had to be done at ambient temperature. Also, the work performed on the growing fracture mouth with the High Pressure Fracture Tester was performed at ambient temperature. The future work will include modifying the equipment for tests at elevated temperatures. Initial indications are that the performance will be improved with temperature effects.

Conclusions

Losses of whole drilling fluid are often encountered when drilling through under pressured, depleted zones. Instead of utilizing large particles to seal natural or induced fractures, this novel approach uses synergistic wellbore strengthening additives to lay down an enhanced filtercake on the wellbore. This allows the wellbore to be continuously strengthened and for the drilling window to be extended avoiding nonproductive time during drilling operations.

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Nomenclature

LCM	= *Lost circulation material*
σ_{Max}	=*Maximum horizontal confining stress*
σ_{Min}	=*Minimum horizontal confining stress*
HPHT	=*High pressure, high temperature*
PPT	=*Permeability plugging tester*
ECD	=*Equivalent circulating density*
NPT	=*Nonproductive time*

References

1. Aadnoy, B. S., Belayneh, M., Arriado Jorquera, M. A., & Flateboe, R. (2008, September 1). Design of Well Barriers To Combat Circulation Losses. Society of Petroleum Engineers. doi:10.2118/105449-PA