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Stabilizing the Complex Ultra Extended Reach Depleted Reservoir Wellbores Using Nano Particles in Water Base Mud System

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Abstract

Around the world, wells drilled through high over balance formations must pass through different pressure zones and often incur wellbore instability and/or losses problems due to lack of proper inhibition from the drilling fluids. The most important variable in maintaining the wellbore stability is the appropriate bridging material selection to avoid wellbore instability and hole collapse. The fractures in the formation are in nano-size levels and products available in the market cannot bridge this rightly leading to bigger fractures and ultimately end up in losing mud causing well control situation and formation damage.

Latest developments in Nano-technology can afford the opportunity to utilise the features of nano-sized particles in drilling fluids where conventional products fail to deliver required wellbore stability. Nano-sized particles are ultra-fine particles (<200 nano-meters) and deformable. They can seal and mechanically plug the micro-fractures thus forming a semi-permeable membrane. This performance attribute prevents fluid invasion, provides support to enhances hole stability by minimizing the pore pressure transmission thus eliminates fracture propagation. This product also helps in minimises the dilution rates, mixing hours, transportation and waste generated.

This paper presents a case history of the latest success of utilizing in two offshore reservoirs in Qatar drilling more than 15,000ft extended reach reservoir wellbore each. This is presented along with the laboratory work carried out during planning phase along with operational experience. Return permeability data shows improved results when compared to a mud system without no nano-particles (NP): minimal lift-off pressure and very low damage to the reservoir.

Introduction

Uncontrolled invasion of the drill-in fluid’s filtrate into a low permeability, porous and micro-fractured formation increases near wellbore pore pressure, potentially leading to the loss of near-wellbore true overbalance pressure and inducing wellbore instability. Therefore, drilling fluid additives, which minimize the rate of fluid invasion, help maintain wellbore stability (Ewy et al., 2008). If not designed properly, the drill-in fluid filtrate can have the most significant impact on the reservoir stability. The practical approach to minimize filtration rate and solids/liquid invasion is based on enhanced pore plugging efficiency achieved by optimization of the bridging agent particle size distribution (Abrams, 1977 and Vickers et al., 2006). Other factors in addition to near wellbore pore pressure increase caused by filtrate invasion are distribution of rock stress conditions and softening (weakening) of the rocks with the use of water-based drilling fluids (Pagels, 2014). Fortunately, new techniques i.e., the use of nanomaterials for fluid invasion control and formation damage control enhance the mitigation of wellbore instability (Riley et al., 2012).

As the drilling efficiency being big focus, wells are being drilled through multiple reservoir targets drilled in a single section. Minimizing the formation damage on these wells can be achieved by using enhanced reservoir drill-in fluids and is key for maximizing hydrocarbon production. During the drilling phase, the filter cake formed on the face of the wellbore should be thin, lubricious, able to prevent mud invasion. This filter cake should be composed of the optimum concentration and size of effective bridging solids and have low liftoff pressure (Gianna et al.,2022). The variable pressure regimes encounter across the wellbore needs to be addressed using Wellbore Strengthening techniques (Aston 2004) to improve the chance of successful well delivery. This usually requires the additional use of non-acid soluble materials, to help generate the hoop stresses required to provide wellbore stability with increased overbalance across the reservoir. Use of these materials are shunned by many operators in an open-hole completion scenario due to their inability to be acidized. Also, where sand screens are proposed, these particles may potentially plug the screens (Chinea., et al., 2023). Work done by Whaley et. Al. (2021) found that the addition of wellbore

strengthening materials may not be as damaging as would be expected. Providing a thin, external filter cake is created quickly then non-acid soluble materials will not penetrate the formation thus not leading to formation damage.
This product was largely used successfully in Saudi-Arabia and Oman to provide Wellbore Stability.

This paper discusses the laboratory study and field applications using Nano particles in Water Base Mud environment.

Product Details

This product is a nano-sized deformable synthetic polymer with packaged particle size (d50: 50 µm) designed to disperse in nano sized particles (d50: 200nm) and seal micro-fractures. It helps to provide enhanced wellbore stability when drilling through high over balance zones or depleted/weak zones. The synthetic nano-sized particles (D50 = 100-200 nanometers) allows the product to enter micro-fractures in the formation thus reducing the fluid invasion and pore pressure transmission.

Benefits

- Better filtration control - Better and faster cake development (PPT, FANN 90)
- Provides pressure shielding - Reduces pore pressure transmission.
- High return permeability - Lower lift off pressure & lower fluid invasion, no production impairment.
- Environmentally benign (CEFAS Gold rated)
- Does not screen out on finest API Screens or in Centrifuges.
- 100% active product, minimizing logistics & footprint on location.
- No loss on shakers due to very low particle size distribution.
- Tolerant to extreme storage conditions
- Lower overall well cost by minimizing the volume to build.

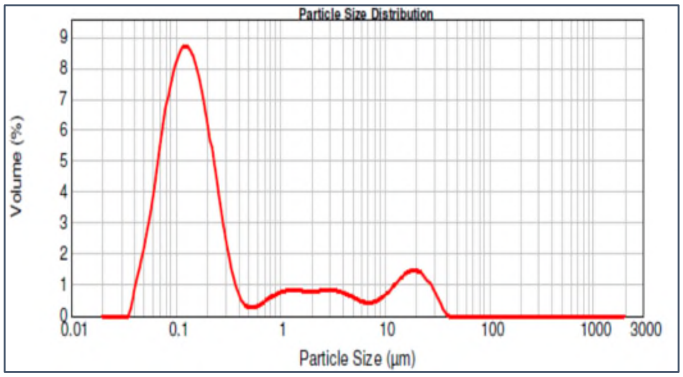

Figure 1: PSD Chart of the product alone

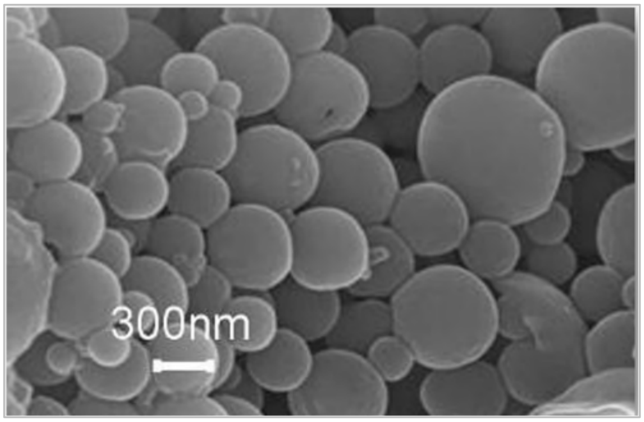

Figure 2: SEM Picture of the Product

Laboratory Work

The objective of lab tests screening is to replicate the actual field downhole conditions as accurately as possible in lab environment and to determine the lower and upper limits for field application of a Pressure Shielding Technology under trial, using the typical LSND for the 8 1/2” sections.

Standard API Mud Check Tests

Below tests were performed for the checking the effect of Nano Particles on API properties (Rheology, API Fluid Loss & pH) of mud system –

a) The tests were to be performed at two stages:
  - Before Hot Rolling
  - After Hot Rolling (Dynamic ageing) for 16 hours at 140°F (BHST)

b) These tests are to be performed with final base mud formulation for comparative analysis.
  - Without pressure shielding products
  - With varying concentration of pressure shielding products to identify the best working combinations

Qualification Criteria:

- No abnormalities in fluid rheology – No drastic increase in PV / YP
- No abnormalities in pH – which remained consistent with no change in rest of fluid formulation.
- 6 rpm reading: 9 to 12
- 3 rpm reading: 6 to 9
- API Fluid Loss < 5 ml/30min

All the formulations were tested at 160°F and 500 psi and reported in **Table 1**. Based on the test results in Table 1, it was decided and agreed to go with 2 ppb NP in the final formulation.

Table 1- Testing of NP and Other Bridging materials on the mud formulation

Products, ppb	Mixing time	F#1		F#2		F#3		F#4		F#5	
8.8 ppg NaCl Brine	-	338.4		338.4		335.0		335.0		333.8	
CAUSTIC SODA	2	0.50		0.50		0.50		0.50		0.50	
SODA ASH	2	0.50		0.50		0.50		0.50		0.50	
STARCH	5	6.00		6.00		6.00		6.00		6.00	
POLYMER VISCOSIFIER	10	1.50		1.50		1.50		1.50		1.50	
COROSSION INHIBITOR I	2	0.50		0.50		0.50		0.50		0.50	
COROSSION INHIBITOR II	2	1.50		1.50		1.50		1.50		1.50	
H_2S SCAVENGER	2	1.00		1.00		1.00		1.00		1.00	
OXYGEN SCAVENGER	2	0.80		0.80		0.80		0.80		0.80	
LUBRICANT	5	10.50		10.50		10.50		10.50		10.50	
CALCIUM CARBONATE SF	10	29.60				28.90				28.20	
CALCIUM CARBONATE FINE	10			29.60				28.90			
NANO PARTICLES	2					3.00		3.00		2.00	
CELLULOSE FIBER SF	5			2.0						2.00	
Test Result		**BHR**	**AHR**	**BHR**	**AHR**	**BHR**	**AHR**	**BHR**	**AHR**	**BHR**	**AHR**
Mud Weight, ppg		9.3		9.3		9.3		9.3		9.3	
pH		10.0	9.5	10.1	9.5	10.2	9.5	10.3	9.5	10.2	9.4
Plastic Viscosity	cP	12	12	13	14	14	13	13	13	13	12
Yield Point	lbs/100ft^2	28	26	29	26	27	26	29	27	28	27
Low Shear Rate		7	5	6	4	6	5	6	4	6	5
Rheology @120°F											
600		52	50	55	54	55	52	55	53	54	51
300		40	38	42	40	41	39	42	40	41	39
200		33	31	34	32	34	32	35	33	33	32
100		24	22	23	21	26	24	25	24	24	23
6		11	9	10	8	10	9	10	8	10	9
3		9	7	8	6	8	7	8	6	8	7
Gel (10 sec/10 min)		9/10	7/8	8/9	6/7	8/9	7/9	8/10	6/7	8/10	7/8
API Fluid Loss											
API Fluid Loss	ml/30 min		2.4		2.2		2.2		2.0		1.8
Brookfield viscosity @ 0.3 rpm	**(x 1000)**										
1 min			19.6		17.5		20.4		18.7		21.1
3 min			22.4		18.4		22.1		20.6		21.6
5 min			23.6		19.5		22.6		21.2		22.5
PPT @ 160°F/500psi/10 micron											
1 min	ml		1.0		2.0		0.6		1.0		0.6
Total Filtrate	ml		9.0		10.8		8.4		9.6		8.0

During the planning stage, fresh LSND mud was received from the field without any treatment with NP. This was the similar formulation used for the NP application in the field.

The results are summarized in **Table 2** and the % reduction in fluid loss properties are shown in **Figure 3**.

The PPA fluid loss was greatly reduced from 16.8 to 8.2 ml.

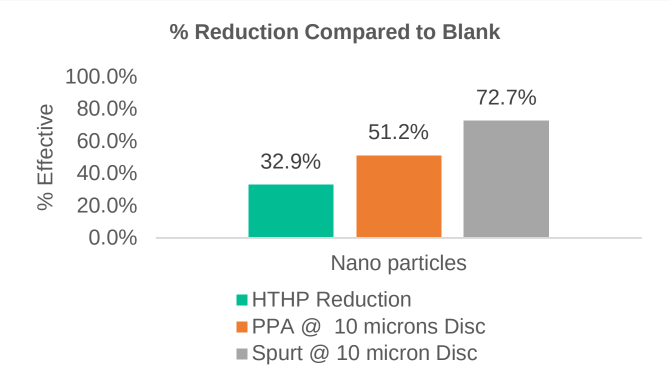

Figure 3 - Showing the % Reduction of Fluid loss properties when compared to Blank on 10 microns Disc.

Table 2- Testing of NP on Field mud sample

	Sample #1	Sample #2
LSND Mud Sample, ml	2 lab bbl	2 lab bbl
Nanoparticles	-	2.0
Cellulose Fiber SF	-	2.0
Properties	**After Hot Rolling at 160F/16 hrs.**	**After Hot Rolling at 160F/16 hrs.**
Mud Weight, ppg	8.8	8.9
pH	9.24	9.22
600 RPM	45	53
300 RPM	32	57
200 RPM	26	31
100 RPM	21	23
6 RPM	9	9
3 RPM	8	8
PV, cP	13	16
YP, lb/100 ft^2	19	21
10" Gel, lb/100 ft^2	8	9
10' Gel, lb/100 ft^2	10	11
API Fluid Loss, ml	3.2	2.2
HTHP, ml (After Double)	15.2	10.2
PPA Fluid loss, ml	16.8	8.2
Spurt loss, ml	2.2	0.6
D5, microns	1.22	1.21
D10, microns	1.83	1.58
D50, microns	11.35	10.11
D90, microns	102.96	158.89

Particle Size Distribution (PSD)

Particle size distribution of all formulations was performed to verify the Dispersion of NP to nano-size and see its impact on low end of PSD.

Mud formulations with Nano Particles were sheared in Silverson High-Shear Mixer at 10,000 rpm for 10 mins. A clear indication of drop in PSD (D5, D10, D50, D90) was observed on addition of NP with peak of NP identifiable in PSD in lab mix mud system (**Figure 4**).

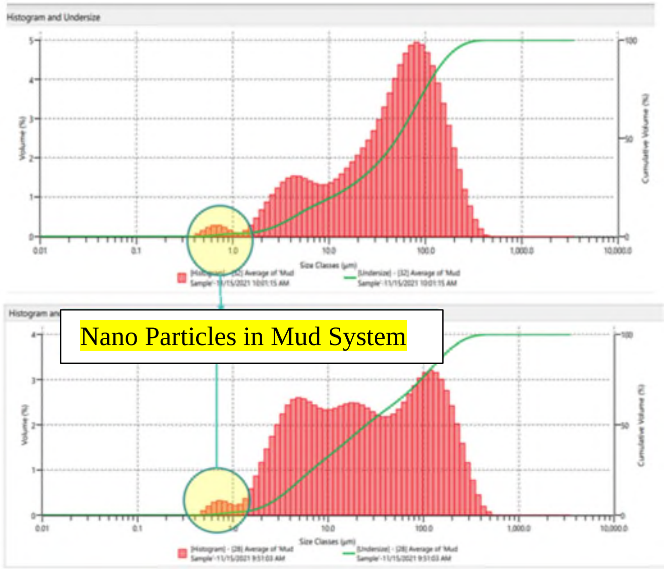

Figure 4 - LSND Formulations with $CaCO_3$ Fine, NP and CFSF

Dynamic Filtration Test

Dynamic filtration tests were run on LSND mud system with and without Nano Particles to evaluate the impact on the dynamic (circulating) filtration rate (DFR) and cake erodibility factor (cake deposition index – CDI).

- **Dynamic filtration rate:** Calculated as the rate of change in the filter volume versus time (ml/min). It can be evaluated over any interval during the filtration process. It is desirable to have a low filtration rate. The rate should be less than 0.2 ml/min for most oilwell drilling fluid systems.

- **Cake Deposition Index (CDI)** – Calculated as the rate of change in the filtration rate versus time [(ml/hr)/hr]. A low CDI indicates that the formation of the filter cake has almost reached steady state. New cake is being deposited at almost the same rate that cake it is being washed away or the additional cake has no effect on filtration. For most oilwell drilling fluid systems, a CDI of 10 ml/hr² or less is desired.

A considerable drop in DFR and CDI was observed on addition of Nano Particles + Fibers to the base fluid system.

Test Parameters:

- Ceramic disc size – 10µ
- Test Temperature – 160 °F
- Differential Pressure – 500 psi
- Shear Rate (Dynamic conditions) – 100 rpm
- Tests carried out after hot rolling for 16 hours at 160 °F

Table 3- Comparative Dynamic Filtration

Parameter	Fluid #1	Fluid #2	Fluid #3	Fluid #4
Fluid Formulation	LSND (Base Fluid)	LSND + 2ppb NP + 2ppb CFSF	LSND + 3ppb NP	LSND + 8ppb Bridging agent + 4ppb CFSF
Dynamic Filtration rate (DFR)	0.0315	0.0207	0.0266	0.0288
Cake Deposition Index (CDI)	11.49	1.76	4.77	6.52
% Reduction in DFR	-	34.2 %	15.4 %	8.6 %
% Reduction in CDI	-	84.6%	58.4%	43.0%

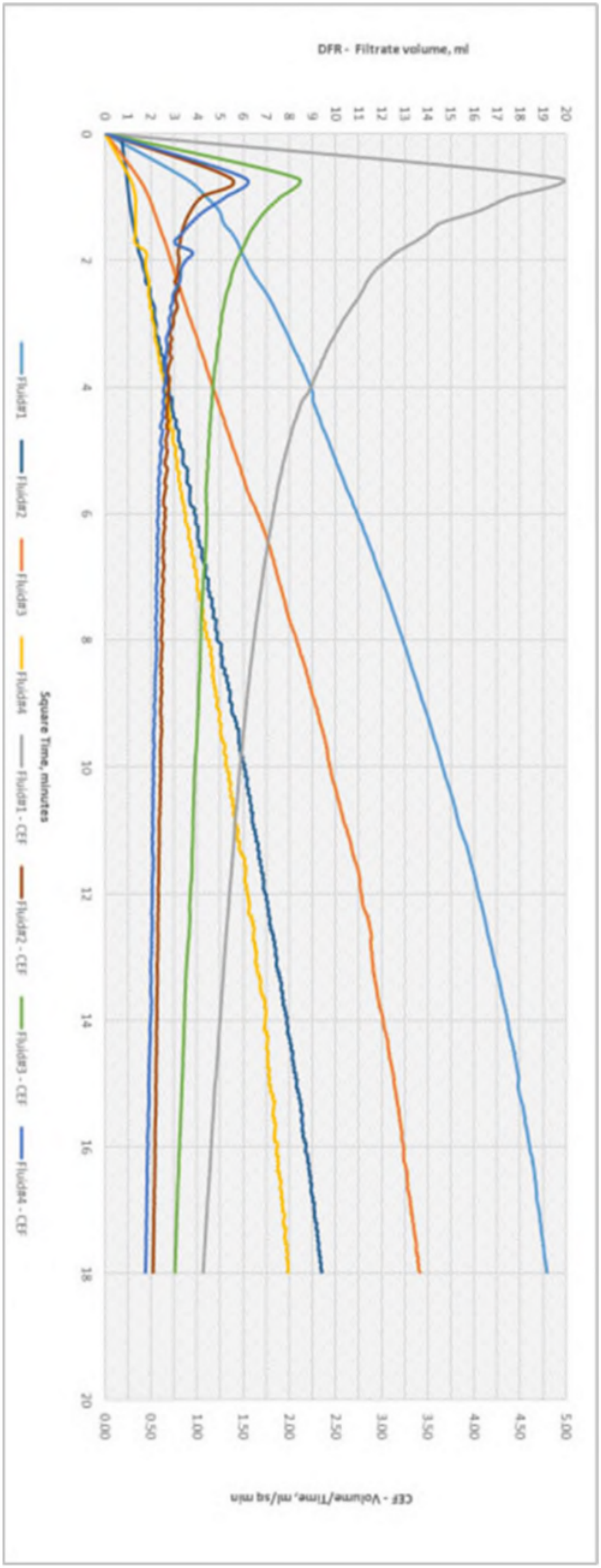

Figure 5 – Dynamic filtration test chart

Return Permeability Testing

Two Return Permeability tests were conducted at higher concentration of the product to understand:

- The overall impact of Nano Particles on formation damage
- Effectiveness of Nano Particles to form a filter cake and limit filtrate invasion.
    - Extent of filtrate invasion in core: This was analyzed by carrying out the return permeability tests with and without Centrifugation. The difference in regain permeability observed without centrifugation and with centrifugation, is indicative of how deep much of fluid and how deep has the filtrate invaded. The greater the difference the greater the invasion.
- Lift off Pressure: lesser the lift-off pressure, easier it is to flow back the filtrate and regain the permeability of formation.

Test Conditions

- Mud Circulation Time: 16 hrs, Mud static time: 12 hrs
- Over balance pressure: 500 psi
- Core Plug type: Indiana Limestone with (9-16 mD) synthetic core
- Test Temperature: 140°F
- Permeability Fluid: LVT-200 - Synthetic formation brine
- Permeability (perm) reading should be captured at every step i.e. Permeability before the mud exposure (Initial) and Permeability after the mud exposure (Final).

Based on the test results (as summarized in **Table 4**):

- Return permeability without centrifugation improved by 17% (77.9% to 95.5%)
- Impact of centrifugation shows
    - LSND: Return perm. increased by 10% - indicative of greater damage due to deeper filtrate invasion
    - LSND + NP: Change in return perm is just 0.8% - indicative of tight filtration control and minimal fluid invasion.
- Reduction in lift-off pressure from 20.7psi to 4.7psi – much easier to lift off deposition by backflowing the well.

Table 4- Summary of Return Permeability Test results

Mud Type	Initial Perm, mD	Final Perm, mD	Regain Perm, %	Final Permeability after centrifugation, mD	Regain Permeability after centrifugation, %
Mud without NP	13.8	11.0	79.7%	12.3	89.1%
Mud with NP	12.4	11.5	92.7%	11.6	93.5%

Having high fluid invasion can lead to interaction with the formation fluids can lead to emulsion blockage leading less production. One of the key properties of NP is to tighten the Spurt loss by having an effective bridging to the formation. In addition, low lift-off pressure of the filter cake is formed across the formation.

The below pictures (**Figure 6a and 6b**) allow the comparison of filter cakes with and without NP. The filter cake with NP is much thinner and demonstrated a very low liftoff pressure. Pictures of the filter cakes on the disc and core were shown below and in Appendices (Fig.17 and Fig.18).

Figure 6 (a) and **(b)** show the Filter cake after the field PPA tests.

Figure 6 (a)- Limestone Core with filter cake for the Mud without NP

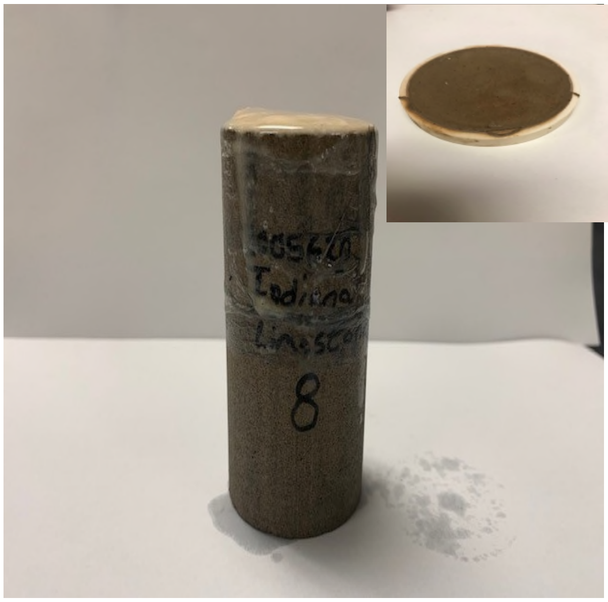

Figure 6 (b)- Limestone Core with filter cake for the Mud with NP

Comparatively, a 4-folded drop (20 psi vs 4.77 psi) was observed in mud filter cake liftoff pressure when comparing both fluids respectively. **Figure 7** & **Figure 8** are the pictures from Return Permeability tests.

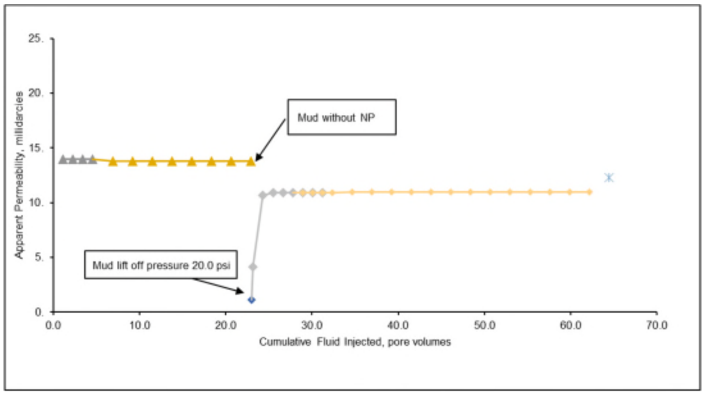

Figure 7 - Showing the Permeability (Before and After) and Mud cake liftoff pressure for mud without NP.

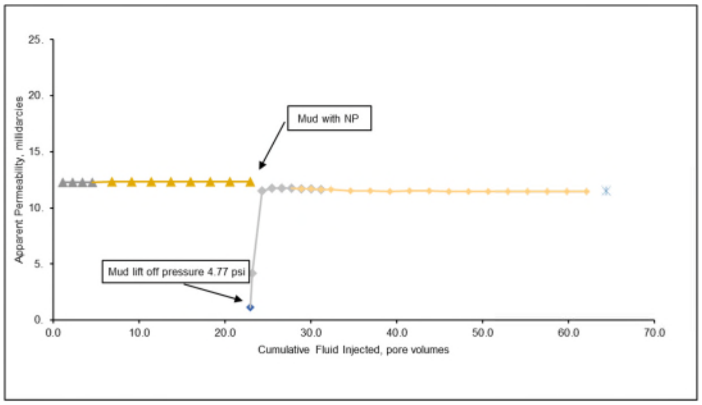

Figure 8 - Showing the Permeability (Before and After) and Mud cake liftoff pressure for mud with NP.

Pore Pressure Transmission Test

Even when the correct mud weight is applied, wellbore instability may still occur with time. The pore pressure transmission test (PPT) measures the tendency of a mud's filtrate, applied at overbalance pressure, to invade the shale fabric and elevate the near-wellbore pore pressure (van Oort et al., 1996).

This "mud pressure penetration" effect can be an important cause of time-delayed shale failure: as near-wellbore pore-pressure goes up, the effective stress state moves progressively towards the failure envelope until at some point in time shear failure will occur. The borehole will enlarge and cavings will show up on shaker screens after several days of open-hole time, followed by operational problems ranging from pack-off and overpulls to full-blown stuck drill string and casing. The effects of mud pressure penetration can be studied in dedicated pressure transmission tests. The PPT test allows for screening of different mud systems for their abilities to block or minimize pore pressure transmission.

This will be represented in Delay Factor (DF) which can be defined as below.

$$\mathrm{DF} = \frac{\text{Hydraulic Conductivity (Pore Fluid)}}{\text{Hydraulic Conductivity (Test Fluid)}}$$

The DF shows the delay in the rate of mud pressure invasion and pore pressure elevation that is expected for a particular fluid system. This delay factor is directly related to trouble-free open hole time, as it indicates by how much of the shale stabilization pressure invasion can be slowed down. Core details used for this test were mentioned in **Table 5**.

Table 5—Core Details on the PPT test performed

Sample Name	Length (in)	Diameter (in)	Weight (gms)	Bulk Density (g/cc)
MR-945_BUR-LS_1H1.A	**0.505**	**1.004**	**17.259**	**2.634**
MR-945_BUR-LS_1H1.B	**0.508**	**1.004**	**17.343**	**2.634**

Test results shows in **Figure 9 (a)** and **Figure 9 (b)**, the mud with NP improved delay factor by 70.5% when comparing the mud without NP (DF = 1.826 vs 1.071 respectively).

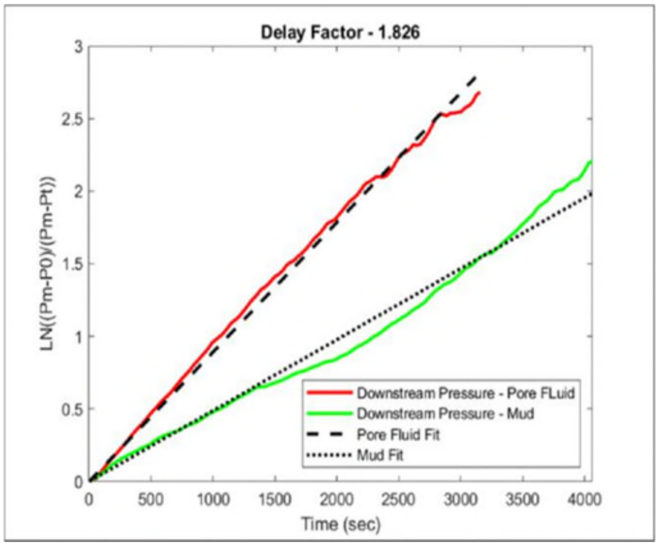

Figure 9 (a) – Delay Factor from PPT equipment for the core sample using mud with NP

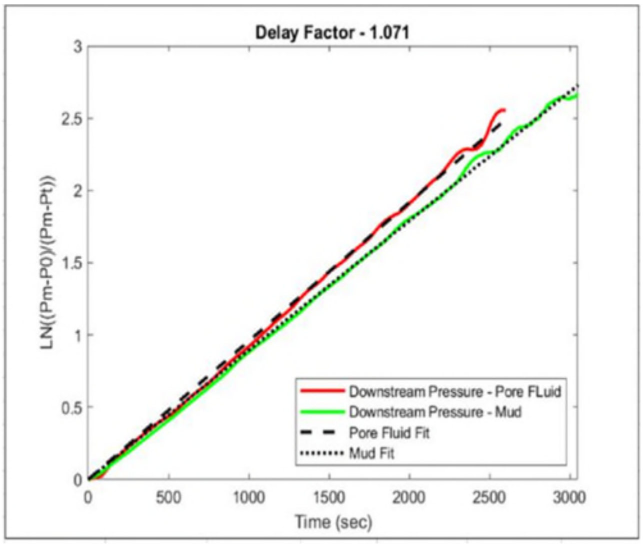

Figure 9 (b) – Delay Factor from PPT equipment for the core sample using mud without NP

Historical data for Pore-Pressure transmission test was studied and evaluated for the effect of NP in reducing pore-pressure transmission on a shale sample.

It was observed that NP was able to effectively reduce the pressure transmitted (**Figure 10)**. Since the Baker Hughes Pore Pressure Transmission test apparatus could not handle added solids to mud system, tests could not be repeated on limestone cores with actual mud system containing $CaCO_3$ Fine. Below test results coupled with tight filtration control formed the basis of qualifying the product for field application.

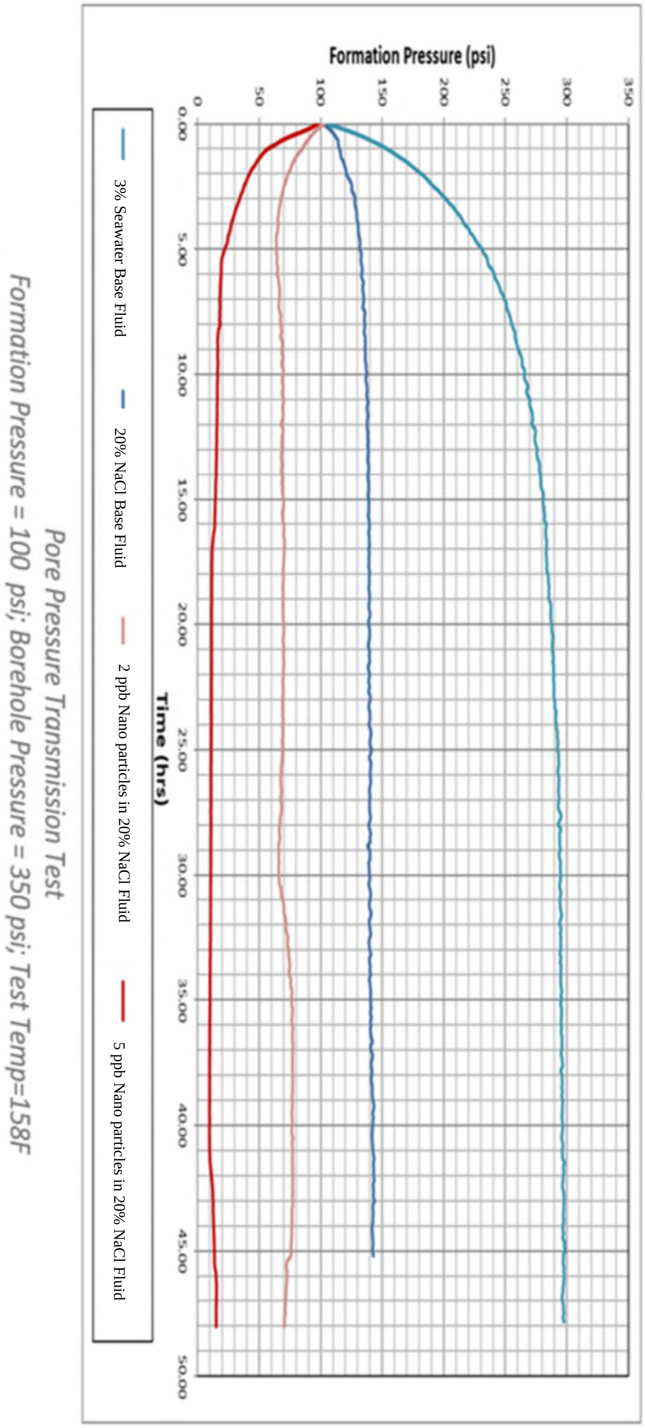

Figure 10 – Pore Pressure Transmission Test Formation Pressure =100 psi, Borehole Pressure = 350 psi, Test Temperature = 158°F

Field Procedures

- **Prepare Concentrated Premix:**
  - A concentrated bridging system pill with 24 ppb NP and 24 ppb Cellulosic fiber Super Fine (CFSF) was prepared in Reserve Pit to be bled into the active during drilling.
- **Mixing and Shearing of NP in Active:**
  - Prior to entering the depleted section, bleed the
  - high concentrated premix into the active mud system to get the system up to spec - 2ppb NP & 2ppb CFSF.
  - Provide a minimum of 2 circulation cycles at 450 to 550 gpm flowrate for the NP to disperse to nano-sized particles. (high shear is required for dispersing NP from 50µ packaged size to less than 1µm nano particles.
  - Run a PPA test with 10µm ceramic disc before and after the addition to observe the drop in Fluid loss. (Fluid loss < 10ml/30min).
  - Treat new mud additions/pre-mix treated with 2 ppb NP / 2 ppb CFSF. Maintain minimum of 2ppb NP in mud system (even if the Fluid loss is considerably below 10ml/30min). A minimum of 2 ppb NP is required in mud system for effective wellbore shielding to prevent pore pressure transmission.
  - Shale Shakers kept at 325 API and centrifuge operating as normal to maintain mud weight.

Table 6 - Pre-Mix Treatment sample calculations

Active Volume (bbl)	Nano Particles Concentration (ppb)	Cellulosic Fiber Super Fine Concentration (ppb)	Nano Particles Required (lbs)	Cellulosic Fiber Super Fine Required (lbs)
1500	2	2	3000	3000
High concentration Premix				
NP Quantity (lbs)	**CFSF Quantity (lbs)**	**NP Concentration (ppb)**	**CFSF Concentration (ppb)**	**Premix Vol Required (bbl)**
3000	3000	24	24	125
Pre-Mix bleed into active				
1 complete cycle		7500		Strokes
Flow Rate		550		gpm
Mud Pump Strokes rate		90		SPM
Time for 2 cycles		169		Minutes
Transfer rate		0.74		bbl/minute

Surface Handling / Mixing

- Prepare a concentrated pill with 25-30 ppb of Nano Particles in Drill Water
- Each sack can be cut and added through mixing hopper slowly. This could be around 1 sack for every 2-3 minutes. Packaged Nano Particles is of 50µm size material (similar to $CaCO_3$ and does not cause any mixing issues or hazard while handling and cutting sacks)
  - No Dusting observed in and around the mixing area
  - Mixing completed very smooth with no wastage of material
- Particle Protective Equipment (PPE) used during mixing was
  - Rubber coversheet
  - P-100 mask
  - Rubber Gloves

Figure 11 – Safe handling And Mixing of Nano Particles

Case Histories

The case studies discussed below are for offshore complex field applications of NP in Low Solids Non Dispersed WBM system in drilling long horizontal ERD sections with high overbalance (up to 800 psi). Concentration of NP in active mud system was based on the spurt loss and total fluid loss in Particle plugging test carried out at regular intervals.

Well # A

Table 7. refers to the well details of the first application of NP in Al Shaheen Field, Qatar Offshore. After drilling the cement and shoe track with previous section mud, the well was displaced with a fresh Low Solids Non-Dispersed (LSND) mud system to drill the 8.5” reservoir section at 6,941 ft. Starting mud weight was 8.9 ppg and which gradually increased to 9.2 ppg as drilling progressed due to incorporation of drill solids from the formation. Continuous dump and dilute with fresh unweighted mud was required to control the mud weight increase. Seepage losses up to 30-35 bbl/hr were prognosed based on offset well analysis in this field. A concentrated NP pill (24 ppb NP) was prepared in reserve pit and bled into active system over 1.5-2 circulations to achieve 2 ppb of concentration of NP before reaching the first high over balance zone. As drilling continued, active concentration of 2 to 2.2ppb of NP was maintained in mud system while keeping the total fluid loss in PPT tests below 10ml. Shale shakers were screened up to API 325 mesh screens and 2 centrifuges were run all the time to maintain the 9.2ppg mud weight. This resulted in reduced dump and dilute requirements and therefore reduced dilution factors. Each time fresh mud was prepared for dilution, it was treated with 2 ppb each of NP to maintain over all concentration in the mud system. During the entire section drilled.

Table 7 - Details for Well # A & Well # B

Job Details		
Well type	Oil Producer	Water Injector
Drilling Fluid System	Low Solids Non-Dispersed Mud	Low Solids Non-Dispersed Mud
Fluid Density (ppg)	8.9-9.2	8.9-9.2
Section Start Depth (ft)	6,941	7,193
Section End Depth (ft)	25,004	25,160
Feet Drilled (ft)	18,063	17,967
Formation Type	Limestone	Limestone
Highest Over Balance (psi)	580	720
Max Inclination (deg)	90.73	91
Hole Size/Liner Size (in)	8.5 / 7	8.5 / 7
Max BHCT (°F)	161	165
Number of Hours, hrs	93	89
ROP Range Achieved (fph)	250-500	250-500

- Section drilled with no signs of differential sticking.
- No incompatibilities with other products in mud system or formation fluids observed. 2% of oil shows from formation observed in mud system.
- Stable torque response during drilling with effective lubricant performance observed in presence of NP.
- No downhole seepage losses observed (possibly due to reduction of pore pressure transmission).

At 25,004 ft, well TD, the hole was circulated till the shale shakers were clean. Back reaming was performed all the way to casing shoe. Observed dynamic losses 5-10 bbl/hr and static losses 1-2 bbl/hr which is less than compared to previous offset wells. The 8.5" hole section was drilled in 5 days.

Particle Plugging Apparatus test was performed at 160°F and 500 psi on 10 microns ceramic disc at the respective depths which shows the total fluid loss was reduced by 32.6% (10.4 ml vs 7.0 ml) and spurt loss was reduced by 54.5% (2.2 ml vs 1.0 ml) and maintained in this range for the complete section drilled. Readings at 7,223 & 7,500 ft shows native mud with no NP. The target range maintenance for this system for Total fluid loss and spurt loss was <12.0 and <3.0 ml respectively. **Figures 12 (a)** and **(b)** shows the Spurt and total fluid loss at different depths during the drilling phase for Well # A.

Figure 12 (a) – Spurt loss from PPA test at different depths for Well # A at different depths during the drilling

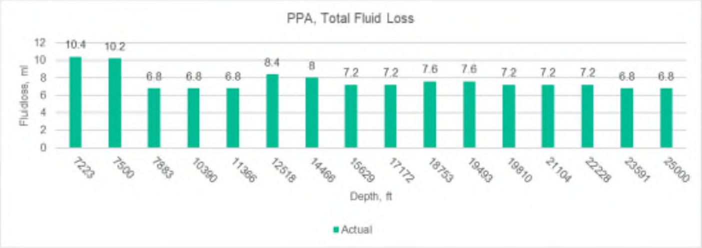

Figure 12 (b) – Total Fluid loss from PPA test at different depths for Well # A at different depths during the drilling

Based on the well results, met all the KPI targets set by the operator before the application and summarized in **Table 8**

Table 8 - KPI's summary for Well # A and Well # B

Properties	Target Range	Units	Well # A	Well # B
Product Concentration	<3.0	ppb	2.0	2.0-2.2
Sample location	-	-	Active System	Active System
Sample Temperature	°F	-	80	110
Density	8.9-9.2	ppg	8.9-9.2	8.9-9.2
Funnel Viscosity	-	sec	44-46	42-47
Plastic Viscosity	ALAP	cP	9-13	9-19
Yield Point	25-30	$lbs/100ft^2$	25-28	25-28
LSYP	4-6	$lbs/100ft^2$	4-7	3-7
pH	10.0-10.5		10.2-10.4	10.2-10.5
Gels (10s/10m)	-	$lbs/100ft^2$	7-9/9-12	7-10/9-12
API Filtrate	<5.0	cc	2.8-4.6	4.0-4.9
PPA Pressure & Temp	160/500	psi&°F	160/500	160/500
PPA Total Fluid loss	<12.0	cc	10.4-6.8	10.4-6.4
PPA Spurt Loss	<2.0	in/32"	0.6-1.2	0.8-1.0
Disc Size	10	microns	10	10
Cake Thickness	1	in/32"	1	1
Product concentration	<3	ppb	2.0-2.2	2.0-2.2
Dilution Factor	<0.5	bpf	0.47	0.46

Well # B

Table 7 refers to the well details of the second application of NP in the same block of Al Shaheen Field, Qatar. After drilling the cement and shoe track with previous section mud, the well was displaced with a fresh LSND mud system to drill the 8 ½" horizontal section at 7,193 ft. Starting mud weight was 8.9 ppg and which gradually increased to 9.2 ppg as drilling progressed due to incorporation of drill solids from the formation like previous well conditions. Continuous dump and dilute with fresh unweighted mud was required to control the mud weight.

A concentrated 24 ppb NP pill was prepared in reserve pit, prior start drilling and bled into the system within 1 full cycle. Before reaching 7,562 ft, where the first high overbalance zone was expected, the active system had been treated with 2 ppb each of NP. While drilling at 13637 ft, observed drop in standpipe pressure due to foam in active pit due to Bi-Carbonates contamination. Observed high pH of 11.5 in active system. Transferred fresh mud to active pit to solve the issue to resume drilling and with dilution, reduced the pH. Treated the active mud system with NP by maintaining an average concentration of 2.0-2.2 ppb to keep the fluid loss parameters in control below 10 ml all the time during drilling. Each time fresh mud was prepared for dilution, it was treated with 2 ppb each of NP to maintain over all concentration in the mud system

Continuously monitored Particle Plugging Test and Particle Size Distribution results while drilling. PPA tests were performed at 160°F/500 psi. The PPA values were maintained within the programmed specifications.

- No downhole losses were observed while drilling and back reaming.
- No sign of differential sticking when drilling or well under static
- Observed 2 % of oil shows in mud from formation and later gradually decreased to 0.5%.
- Added lubricant in 1% increments from 18,800 ft to achieve a concentration of 3 % by vol. by and was maintained till TD.
- No downhole seepage losses observed (possibly due to reduction of pore pressure transmission).

At 25,160 ft well reached TD, circulated hole clean till the shale shakers were clean.

Particle Plugging apparatus test was performed at 160°F and 500 psi on 10 microns ceramic disc at the respective depths which shows the total fluid loss was reduced by 39% (11.2 ml vs 6.8 ml) and spurt loss was reduced by 71.4% (2.8 ml vs 0.8 ml) and maintained in this range for the complete section drilled. Readings at 7,308 ft shows native mud with no NP. The target range maintenance for this system for Total fluid loss and spurt loss was <12.0 and <3.0 ml respectively. **Figures 13 (a)** and **(b)** shows the Spurt and total fluid loss at different depths during the drilling phase for Well # B.

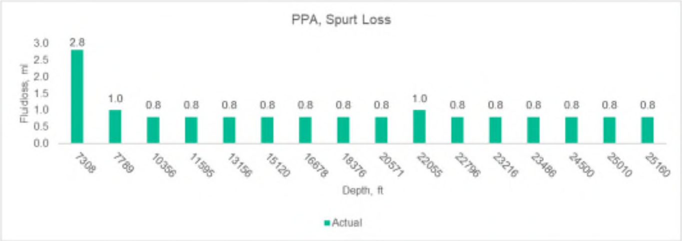

Figure 13 (a) – Spurt loss from PPA test at different depths for Well # B at different depths during the drilling

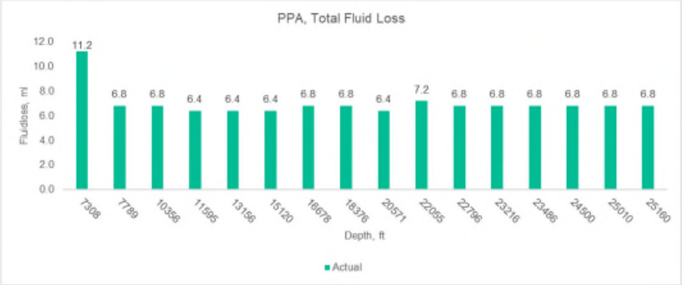

Figure 13 (b) – Total Fluid loss from PPA test at different depths for Well # B at different depths during the drilling

This section achieved a record drilling of 7,501 ft in 24 hours and broke the previous record of 7,335 ft in this field.

Based on the well results, met all the KPI targets set by the operator before the application and summarized in **Table 8.**

Torque

The addition of NP was not detrimental to the Torque values, nor beneficial to reduce the Torque, as shown on the **Figure 14**, when comparing the Trial Wells with Offset Wells.

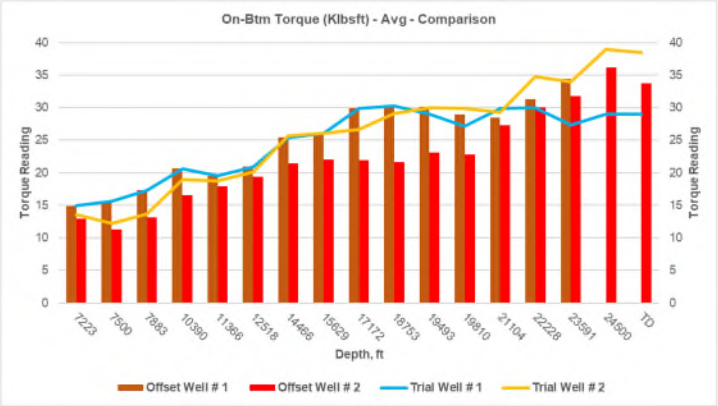

Figure 14 – On-Bottom Torque Readings Chart comparing Trial wells (Lines on Right axis) with Offset Wells (Bars on left axis)

Conclusion

Adding NP for Wellbore strengthening and pore pressure transmission to an open hole completion well didn't cause any formation damage based on the return permeability data provided. This was backed up by the well production and injection rates respectively.

NP didn't have any degrading effect on mud rheological properties and on the Torque Values.

Particle Size Distribution of Mud didn't show any difference before and after adding NP. This is due to shadowing of bigger particles present in mud system (Calcium Carbonate and Drill solids).

No Non-Productive Time (NPT) were reported during both well executions.

Performing Pressure Shielding with NP was very beneficial for the case histories presented. Summary showing in **Table 8** confirming, all the Key Performance Indictors (KPI's) for the wells set forth before the well start met the target.

Multi zone completion liners were run successfully in the first run on such long laterals of 18,000 ft approximately.

Considerable cost savings were achieved by replacing the existing technology with NP with less dilution rates.

Reduced GHG emissions due to product usage reduction.

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Nomenclature

- AHR = After Hot Rolling
- API = American Petroleum Institute
- BHR = Before Hot Rolling
- BHST = Bottom Hole Static Temperature
- $CaCO_3$ = Calcium Carbonate
- CDI = Cake Deposition Index
- CEFAS = Centre for Environment, Fisheries and Aquaculture Science
- CFSF = Cellulosic Fibres Super Fine
- cP = Centipoise
- DF = Delay Factor
- DFR = Dynamic Filtration Rate
- ERD = Extended Reach Drilling
- °F = Fahrenheit
- ft = Feet
- gpm = Gallons per Minute
- hr(s) = hour(s)
- KPI = Key Performance Indicators
- LSND = Low-Solids Non-Dispersed Mud
- PPA = Particle Plugging Apparatus
- ppb = Pounds per barrel
- ppg = pounds per gallon
- PSD = Particles Size Distribution
- psi = Pound Force per Square inch
- mD = MilliDarcy
- min = minutes
- ml = millilitres
- NP = Nano Particles
- NPT = Non-Productive Time
- Perm = Permeability
- PPT = Pore Pressure Transmission
- PV = Plastic Viscosity
- YP = Yield Point
- rpm = Rotations Per Minute
- SEM = Scanning Electron Microscope
- SF = Super Fine
- SPM = Strokes Per Minute
- TD = Terminal Depth
- WBM = Water-Based Mud

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Appendixes

Figure 15: Picture showing Dry product
Figure 16: 2 ppb NP Fully Dispersed in 20% NaCl brine
Figure 17: Filter cake without NP
Figure 18: Filter cake with NP
Figure 19: OFITE Particle Plugging Apparatus
Figure 20: Portable Particle Size Analyzer

Figure 15 - Dry Nanoproduct

Figure 16 - 2 ppb NP Fully Dispersed in 20% NaCl brine

Figure 17 - Filter cake without NP

Figure 18 - Filter cake with NP

Figure 19 – OFITE Particle Plugging Apparatus

Figure 20 - Portable Particle Size Analyzer