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Paving the Road While Driving: Changing Mud Design While Drilling

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Abstract

The purpose of this paper is to introduce a new methodology that was used in drilling power water injector well to encounter seepage losses and sticking issues. The introduced method will pave the path for the construction of a smart platform to link mud design and rock characterization. The platform will be used to select, deploy and maintain a fit-for-purpose bridging package in the mud while drilling. Upon the incidents of repetitive sticking and overpull while drilling the 6-1/8" horizontal section, a comprehensive review of several data was performed and three stages method was developed to encounter the aforementioned challenged. The three stages consist of analyzing the mobility logs, Mercury Injection Capillary Pressure (M.I.C.P.) data and permeability ranges from logging. Consequently, a modification in bridging strategy was implemented "on-the-fly" for the high-performance oil-based mud. These stages are key inputs to construct the smart platform which will provide directions on a timely manner for additions while drilling, screens management and the deployment of fast-response pills by real time monitoring. In addition, the smart platform will include a software to assist in the mud design for targeting pore throats and micro-fractures. Through the developed process, mud formulations were re-engineered accurately for minimizing fluids invasion, reducing fluids friction coefficient factors, prevent differential sticking issues and mud cake lubricity. As a result, better drilling performance was achieved, contributing in more successful holes, completion screens deployed on bottom and injection rates exceeded. The concept was well proven for delivering successful power water injector wells.

Introduction

A non-damaging mud is required for drilling the reservoirs sections, with an appropriate control on fluids invasion. Therefor an engineering process is in place for the mud design, in order to tackle all operations risks, such as differential sticking and mud losses, among others.

Drilling fluid design and monitoring execution are essential to reduce the risk of stuck pipe. The following key points should be considered when designing and executing a well where high permeability zones are expected and risk of differential sticking is high.

- Magnitude of the Overbalance. Minimization of overbalance, depending upon data from latest pressure and sampling logs, including hole stability model and mud weight window.
- Drilling Fluids type. Oil-based mud (OBM) will reduce the risk of differential sticking compared to Water-based Mud (WBM). Filter cake quality plays a major role. Due to lowest filtration rates and more controlled fluids invasion, OBM is the best mud system to select and Flat Rheology Oil-based System (F.R.O.B.S.) has been chosen for drilling into clean sands.
- Bridging the Pore throats of the permeable formation, as clean sands. This is a critical aspect of the fluids design, by using adequate particles background for a fit-for-purpose filter cake construction, based on material composition and sizes.
- Rock characteristics. Pore throat sizes and permeability data. Mercury Injection Capillary Pressure (M.I.C.P.) from formation cores can provide particle pore throat sizes distribution. Moreover, new mobility logging runs can confirm any change in permeabilities. Indeed, MICP and permeability logs are reliable sources of information used for better understanding on rock characteristics.
- Quality of the filter cake and filtration rates. When solids penetrate formation, permeability will be reduced during the filtration process as seepage losses, while cake is being formed. Once cake is fully deposited, it should be thin, impermeable and strong enough to control any further filtration into sands while drilling. Filter cake is verified at static (Permeability Plugging Test) and Dynamic conditions (Fann 90 or equivalent).
- Methodology for selecting the bridging package. Choosing the approach to select a bridging package to fit rock characteristics is crucial, based on how pore throat sizes are uniform among reservoir of interest. Vickers (Vickers et all. 2006) is an advanced approach where particles selection must satisfy some particle size distribution values for an adequate bridging, and has been adopted for this study based on the available information from M.I.C.P. data. If M.I.C.P. information is not available, use Ideal Packing, by selecting median size with the square root of the permeability.
- Measurement of the bridging ability of the fluid and running a bridging system in the field. The effectiveness of the bridging strategy is measured with the Permeability Plugging Test (PPT), maintenance of particles in the mud and minimization of seepage

losses while drilling.

  - Differential pressure for testing must be 500 psi above maximum overbalance.
  - Values for OBM will be likely to be lower than for WBM.
  - Permeability Plugging Test values are pre-defined and monitored at rig site by mud engineers.
    - Particle Size Distribution (PSD.) to be monitored at Liquid Mud plant or lab in town.
    - PSD can be monitored at rig site by using portable analysers.
  - Disc selection for PPT to be based on rock pore throat size D50 (median) as normal PPT and control PPT (contingency), based on D90 (90 % of the particles below this value).

- Attrition of particles. A difficult aspect of the treatment is the addition of bridging particles. These are low gravity solids to be added the mud, which with time will grind down and no longer provide an efficient bridging (development of fine and colloidal particles), affecting mud rheological properties and equivalent circulating densities.
  - Use strong nature bridging materials as marble (metamorphic rock) due to its extent resistance towards attrition. Do not use limestone or calcite (sedimentary rock).
  - X-Ray diffraction (XRD) test can detect hematite or gypsum, which are basically sedimentary rocks.
- Adequate Drilling practices. Minimization of cuttings annulus load and allowing construction of filter cake and implementation of sticking test are critical.
- Screens selection. Choose API screens size with D100 cutting point (100% separation), as per API 13C designation for drilling.
  - Avoid using mud cleaner. It will promote particles disintegration and formation of fines and colloids.
  - Do not screen up for Production Screen Testing (PST), before running lower completion.
- Dynamic filtration and cake deposition testing. This testing is critical for better understanding on the effectiveness of the briding and sealing package in the mud under dynamic conditions, with a shaft and paddle are extended down into the fluid to simulate downhole conditions and create a filter cake at the face of a synthetic core with a well known permeability. At the same time is eroded in order to qualify the cake deposition index, until reaching equilibrium between deposition and erosion and keep a filtration rate steady.

Flat Rheology Oil-based system)

Oil-based Mud formulations from different fluid providers with no progressive gels have been used for drilling overburden and reservoir sections, selected for Equivalent Circulating Density (ECD) management. Depending upon required mud density and Oil-Water Ratio (OWR), mud formulations have been optimized and standardized allowing to predict hole cleaning with accuracy, minimize fluids invasion and protect formations being drilled. However, barite is not used in the mud formulations for the reservoir sections but only marble – sized, as acid soluble weighting and bridging material. The major application for Flat Rheology Oil-based systems is for more complex wells classified under the narrow pore pressure and fracture gradient window, minimizing the risk of hole instability and induced mud losses caused by the adverse elevation of viscosity and the consequent increase in Equivalent Circulation Density, as a function of temperature and pressure. Furthermore, with F.R.O.B.S, we have seen improved rate of penetration and minimization of differential sticking while drilling into shallow reservoirs. Finally, minimization of layout required for deck space for chemicals storage and less mud maintenance, compared with Conventional Oil-based systems. The following are the general drilling fluids specifications:

Drilling fluid formulation	**Concentration range**
Mineral Oil	For 75/25 - 80/20 OWR
Water	For 75/25 - 80/20 OWR
Emulsifier	7 – 11 ppb
Wetting/Second emulsifier	1 – 3 ppb
Viscosifier	3 – 6 ppb
Filtration Control	2 – 4 ppb
Rheological Modifier	1 – 3 ppb
Calcium chloride	For 250 – 260 K mg/lt chlorides
Marble fine	For 11 – 11.4 pcf mud density
Marble M	7 – 10 ppb
Marble – 25 microns	5 – 7 ppb
Marble – 25 microns	5 – 7 ppb

Table 1a. Drilling fluid general formulation.

Mud properties	**Range**
Density, pcf	11 – 11.4 ppg (82 – 84 pcf)
PV, cp	ALAP
YP, lbs/100ft^2	18 – 22
10"/10'/30' Gels	9-11 / 14-18 / 17-20
LSRYP, lbs/100ft^2	7 – 8
HPHT (500 psi & 250 °F), cc/30 min	Less than 3 ml
Electrical stability, v	450 – 650 (No water in the filtrate)
OWR, Ratio	75/25 – 80/20
PPT (20 & 35 microns, and 55/60 microns and 90 & 120 microns, 1500 – 2500 psi & 250 °F)	Spurt to be less than 1 ml Total to be less than 3 ml
Cake thickness (PPT), 32nd inches	1/32 inches
PSD, D10/D50/D90, microns	3-5/20-30/50-60
PST	No plugging
Drilled Solids	Less than 3%

Table 1b. Drilling fluid general properties.

Protecting formation from fluids invasion

Aiming to maximize the reservoir productivity and injectivity, in larger exposure of reservoir area increase the technical demands for project execution. Such demands are different in each step of the operation and require various engineering strategies to deliver a well. The reservoir needs to be protected to minimize the possibility of reducing its productivity and increasing injectivity. Such protection requires detailed design using materials that are reservoir friendly and adequate solids to bridge the reservoir pore throats. Additionally, the wellbore needs to remain stable for elongated periods of time, so drilling is completed. Such targets are achieved through the combination of fit-for-purpose drilling fluids systems, loaded with adequate bridging materials. These materials are selected from pore throat modeling software, used to design a given particle size distribution from a combination of bridging agents, assuring minimum fluid invasion into reservoir. In order to achieve the final target of completing the section without incurring in costly mud losses and differential sticking events, an improved bridging package by using calcium carbonate sized, based on software simulation must be deployed while drilling.

The tripping operations that occurs after the wells reach their Total Depth (T.D.) to remove the drilling string and later when running lower completion equipment to T.D. require having a wellbore that is spotless clean, stable and formation protected for the whole period the hole is left open. These are fundamental steps to run lower completion to bottom smoothly without sticking tendencies. This engineering approach enabled to complete multiple reservoir sections, minimizing mud losses, preventing stuck pipe incidents and maximizing productivity or injectivity into clean sands.

Sticking test procedure

Sticking tests are frequently required to early detect any potential differential sticking tendencies across the reservoir. If so, filter cake should be re-built, by allowing good enough circulation. Normally sticking tests are conducted before logging, before performing the formation pressure test and formation fluids sampling with pipe, run into the hole to approximately 20 ft above the required depth, slack off and pickup values are to be recorded into the sticky test sheet, then correlate and perform sticky test for 5, 10 and 15 minutes. If overpull is seen more than 25 kips over the initial recorded values, points to be aborted and proceeded to next points for logging.

- The maximum stationary time during pressure points is 30 minutes.
- Reciprocate pipe as required prior to proceeding tests after time limit is reached. In addition, sticking test can be conducted while making connection.
- If sticking test shows any tendency of sticking proceed to pump sealing pill, before making the connection.

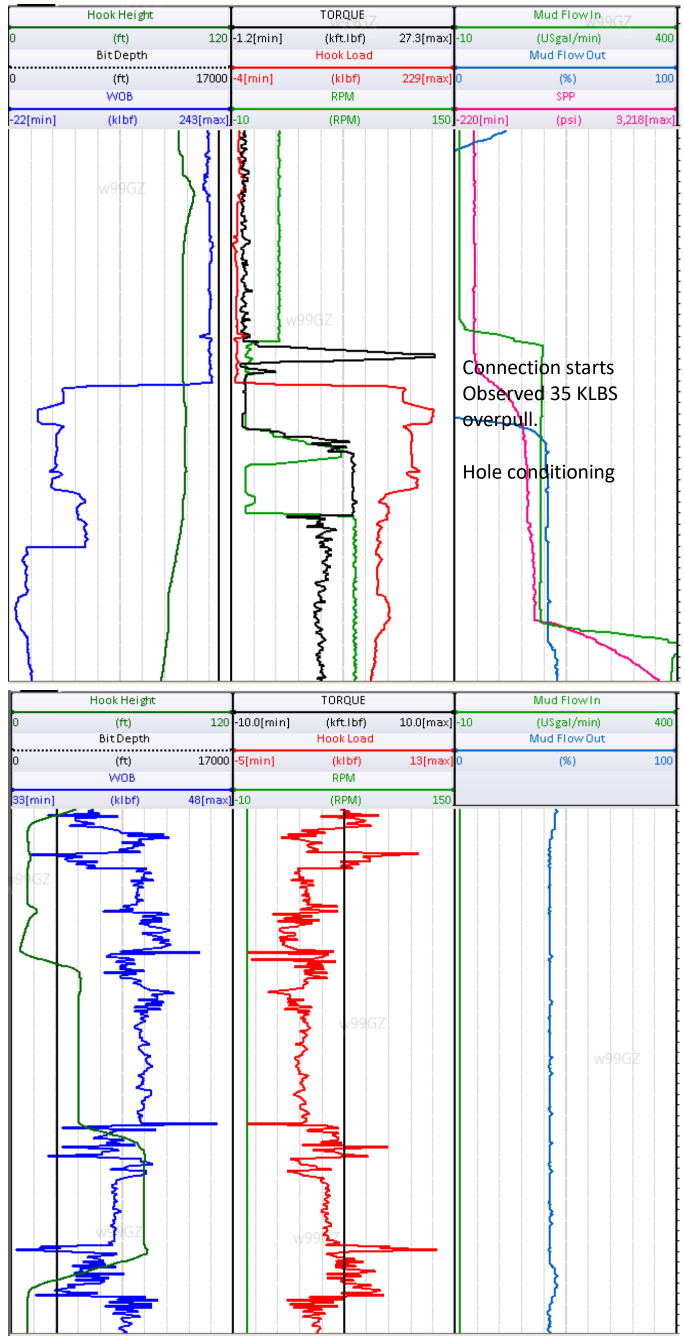


Figure 1a & 1b. Sticking trend observed initially and parameters for POOH without issues

After circulated hole clean, production screen test and flow check operations were conducted. P.O.O.H. with reaming bottom hole assembly and observed 35 KLPS overpull after connection. Circulated to condition the hole and treat active mud system as per fluid specialist recommendation, as per figure 1a. Continued P.O.O.H. and ran into hole 5 stands, washed and reamed, circulated hole clean, without issues, as per figure 1b.

Triggering the change in mud design

This is a summary of the events. In the first well of the platform located on s flank position, drilled with 11.4 ppg (84 pcf) barite-free Flat Rheology Oil-based system (F.R.O.B.S.) and logged the first 6 1/8" x 7 ¼" horizontal hole through clean sands at a controlled Rate of Penetration (R.O.P.), conducting stick test with no overpull before pressure points. While drilling, kept a very tight control on PPT and no seepage losses by using 20 microns ceramic disk with 1500 psi differential pressure (500 psi above maximum expected overbalance), by loading active mud system with 20 pounds per barrel (PPB) of particles, as follows: 5 PPB of Calcium carbonate 25 microns, 5 PPB Calcium carbonate 50 microns and 10 PPB of Calcium carbonate 150 microns.

After reaching well total depth (T.D.), changed Bottom Hole Assembly (B.H.A.) and condition the hole, by reaming last three stands and sweeping with high weight pills. Then, circulated until hole clean and conducted a positive Production Screens Testing (P.S.T.) and pull out of the hole, observing high overpull after connection. Circulated and condition F.R.O.B.S. as per fluid specialist recommendation.

Higher permeability values were confirmed from mobility logs from other offset wells, and bridging strategy was modified on the spot, by using 7 PPB of Calcium carbonate 25 microns, 7 PPB Calcium carbonate 50 microns and 6 PPB of Calcium carbonate 150 microns, and screens were changed for allowing to keep particles background in the active mud system. Circulated bottoms hole clean, spot a beads pill, P.O.O.H., and ran lower completion to bottom. Same bridging strategy combined with the use Seal – Go pills before sampling and pressure points logging was implemented in the upcoming 6 1/8" horizontal holes, drilled without overpull navigating through same formation and following new drilling practices, as sticking test and circulating for allowing cake to re-build. Therefore, planned injectivity rates were exceeded and three subsequent wells were delivered successfully by adopting the new drilling fluid strategy.

A lesson learned allowed to develop a process for the mud design during planning and monitoring during execution. This process triggered the application of an integrated software package used to design a given bridging strategy based on reservoir rock properties from a search engine and monitor mud invasion – related properties while drilling, in order to verify and adjust particles background in the active mud system when required.

Previous vs New mud design

Based on old available information, a bridging strategy was considered for drilling horizontal holes into clean sands, as below:

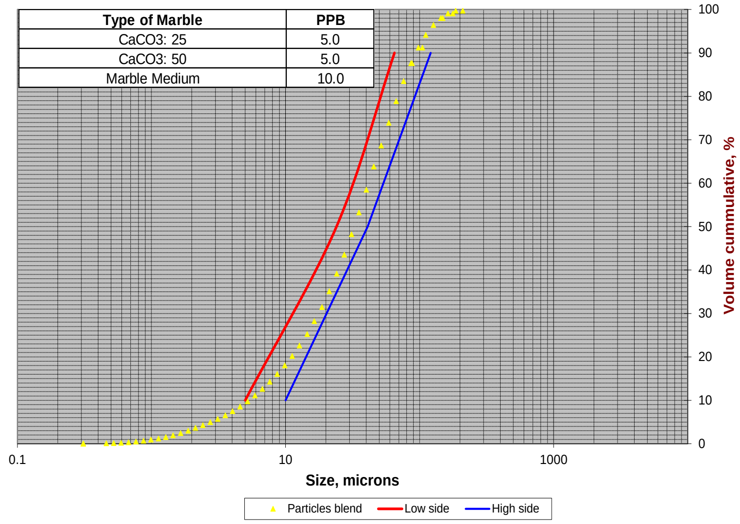


Figure 2a. Planned Particle Size Distribution (previous design)

Red line and blue lines represent the lower and upper limit of the pore throat sizes. Yellow dotted-line is the particle size distribution (PSD) of the blend of different calcium carbonate sizes in a PSD vs Volume cumulative plot, in an average concentration of 20 PPB.

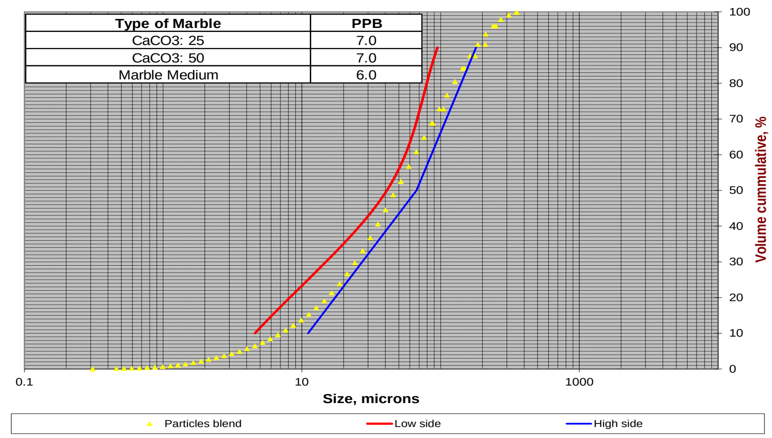


Figure 2b. New Particle Size Distribution

20 microns disk was selected for PPT initially, based on a given range for permeability. With the new information for permeability from mobility logs and review on other M.I.C.P. data, a new bridging design was required while drilling and PPT disk were changed to 55 - 60 microns, in order to fit higher rock permeabilities. In addition, a fluid strategy in place did allow to build and maintain a particles background in the active mud system while conditioning the hole, based on:

- Hourly additions were required to keep a tight control on PPT filtration as per mud management operations (Figure 3) and to compensate what the formation is taking and loss of sizes due to particles attrition.
- Shale shakers screens were changed from API 200 – 230 to API 140 - 170.

- Pumping and spotting 10 – 20 PPB Seal-go pills were spotted before P.O.O.H. for logging (pressure points or fluids sampling) or for changing B.H.A.

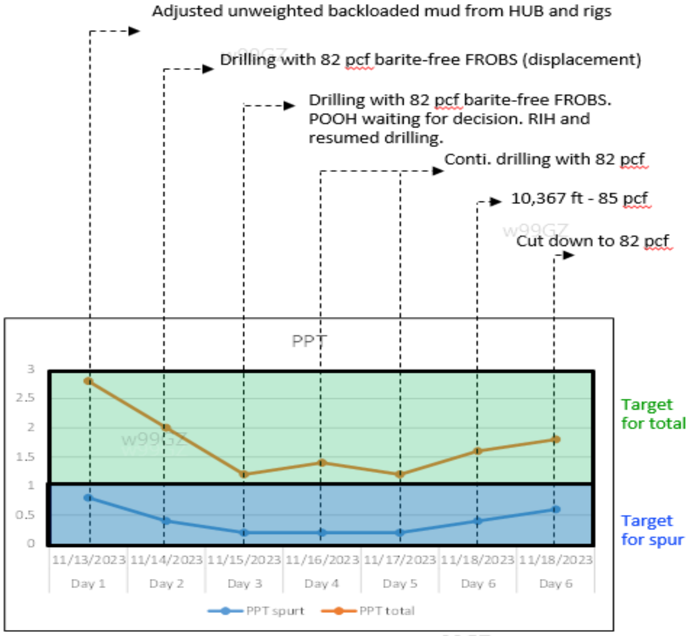


Figure 3 *Close follow up on PPT filtration behavior. PPT Ceramic disk used for Days 1, 2 and 3 were 20 – 35 microns. It was changed to 55 microns afterward.*

Monitoring while drilling

Determination of the real particles background in the mud system and specialized testing as dynamic filtration while drilling are meticulous analysis and offer a number of challenges due to availabiulity of equipment and location, and limitation for installation in offshore rigs (i.e. PSD analyser).

- Permeability Plugging Test is a filtration control test conducted at downhole conditions at the rig site, where the filtration mean is a ceramic disk. PPT filtrate and filter cake were closely monitored and reported daily through a PPT tracking sheet (Figure 4). Reported values for spurt/total values for previous and new mud design were: 0.4/2.4 cc and 0.2/1.4 cc.

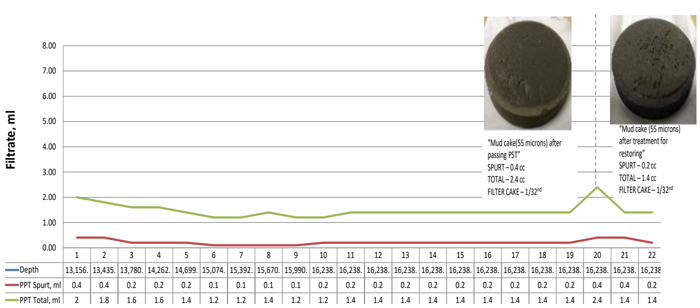


Figure 4 *Adjustment in PPT ceramic disk (previous vs new mud design).*

- Furthermore, particle size distribution was evaluated for the new mud design, by using Laser Diffraction and provide a probabilistic distribution of the particles on given mud samples collected from returns, after solids control equipment and at suction tanks for better understanding on impact of solids removal and particles attrition (Figure 5a and 5b). Mud samples were transported and evaluated at the liquid mud plant.

11 ppg (82 pcf) barite free F.R.O.B.S. formulation was modified during a 2 total cycle of circulations (estimated two hours) via hourly additions and screens were open for allowing to keep the required particles in the active mud system, and samples were collected for PSD. analysis.

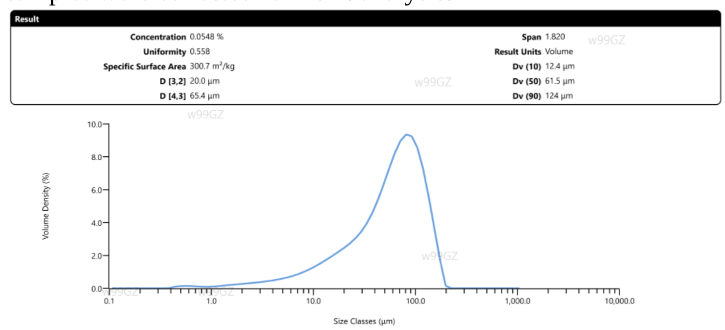


Figure 5a. 11 ppg (82 pcf) barite-free mud collected for PSD at 9:30 am.

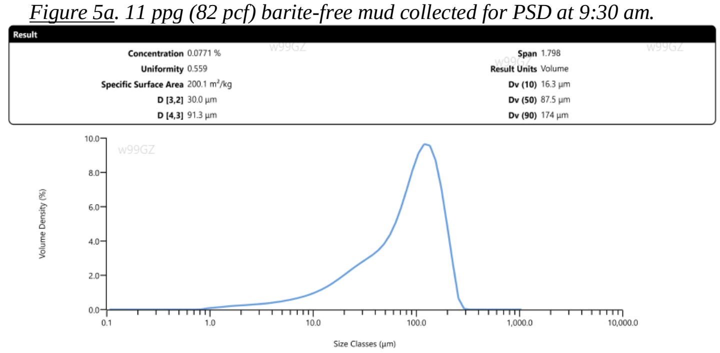


Figure 5b. 11 ppg (82 pcf) barite-free mud collected for PSD at 11:30 am.

A post analysis on mud samples for the previous mud with the old bridging package design and the new foprmulation, allowed us to understand the dynamic filtration ocuurred, at the laboratory:

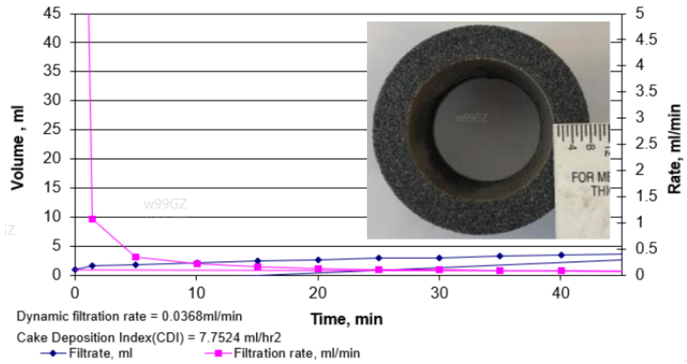
- Dynamic filtration through Fann 90 (Figure 6) for simulating for cake deposition is measured as well, by using specialized laboratories in town.
  - The dynamic filtration rate does represent the pluggin ability of the mud. A lower rate indicates a mud with good plugging ability.

$$\text{Rate, ml/min} = \frac{\text{volume at 45 min} - \text{volume at 20 min}}{25\ \text{min}}$$

  - The C.D.I. reflects the rodability of the filter cake and it is based in the filtration rate over time. If the filtration rate is stable, the cake thickness is constant.

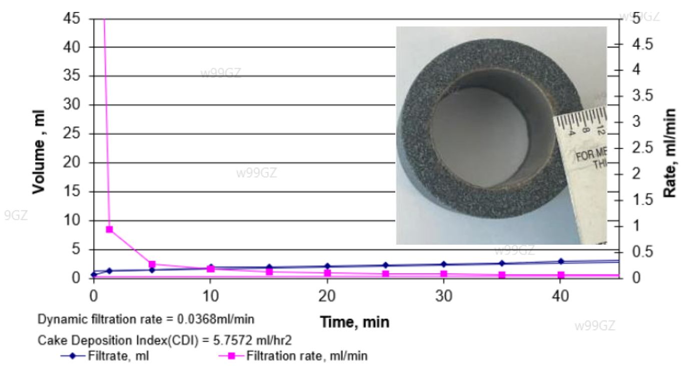
$$\text{CDI, ml/hr}^2 = \frac{\text{rate at 45 min} - \text{rate at 20 min}}{25\ \text{min}} * \frac{3{,}600\ \text{min}^2}{\text{hr}^2}$$

- For 11 ppg (82 pcf) OBM (previous mud design with 20 microns disk), the total filtration volume after 20 minutes and 45 minutes were 2.68 and 3.60 cc respectively, with a dynamic filtration rate of 0.0368 ml/min and a cake deposition Index (C.D.I.) of 7.7572 ml/hr^2 .



6a

- For 11 ppg (82 pcf) OBM (new mud design with 55 microns disk), the total filtration volume after 20 and 45 minutes were 2.18 and 3.1 cc's respectively, with a dynamic filtration rate of 0.0368 ml/min and a cake deposition Index (C.D.I.) of 5.7572 ml/hr^2 .



6b

Figures 6a and 6b. Dynamic filtration tests results (Fann-90), for better understanding on time for cake construction, with photos of the 20 and 55 microns ceramic disks, for mud with previous design vs mud with new design .

	Previous 11 ppg Mud formulation	New 11 ppg Mud formulation
Dynamic Filtration Rate, Rate for 9.1-12 ppg ≤ 0.22 ml/min*	0.0368 ml/min @ 20 microns	0.0368 ml/min @ 55 microns
CDI, CDI for 9.1-12 ppg ≤ 25 ml/ hr^2*	7.75 ml/ hr^2	5.7572 ml/ hr^2
PPT spurt and Total, Spurt ≤ 1.0 & Total ≤ 3.0 ml	20 microns (Control disk): 0.4 & 2.0 ml 35 microns (spot check disk): 0.8 & 2.6 ml)	55 microns (Control disk): 0.2 & 1.4 ml 90 microns (spot check disk): 0.4 & 2.4 ml
PSD, D10/D50/D90 3 - 5 / 20 – 30 / 50 - 60 microns for old mud design 5 - 10 / 60 – 90 / 120 – 180 microns for new mud design	4.5/22.1/57.3 microns	12.4/61.5/124 microns 16.3/87.5/174 microns

**As per Maximum recommended Filtration Rate and Cake Deposition Index guidelines.*

Table 2. Summary of the reported properties for Filtration Rate, Cake Deposition Index, Permeability Plugging test and Particle Size Distribution for previous and new mud design.

Conclusions

- Building an integrated hardware and software system would allow fulfilling operational needs. This can be achieved using the available reservoir data in designing proper drilling fluid, managing the particle size distribution in real time and implement adjustments on the fly to fit continuously reservoir petrophysics.
- Available reservoir data allowed to optimize drilling fluids design, fluid invasion was minimized, protecting reservoir and preventing stuck pipe. In addition, it allowed to complete logging program, including pressure points of formation fluids sampling, deployment of lower completion on bottom and exceeding planned injection rates.
- Approach was verified at the laboratory, through specialized testing, where particle size distribution, dynamic filtration rates and Cake Deposition Index for the drilling fluids formulations used previously and the new bridging strategy design.

Nomenclature

- ml/min; referred to filtration rate in milliliter per minute
- PPB; referred for product concentration in Pounds per Barrel.
- ml/hr^2; milliliter per hour in one hour; referred to Cake Deposition Index
- PPT; referred to Permeability Plugging Test at rig site
- PSD; Particle Size Distribution
- ECD; Equivalent Circulating DensityDepending
- OWR; Oil-Water Ratio in the mud
- PST; Production Screen Testing

References

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