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Successful Application of Synthetic Graphite to Overcome Severe Lost Circulation Problem in the Troublesome Foothills of Colombia

Mario Ramirez, Baker Hughes Drilling Fluids, Asdrubal Diaz, BP Colombia, Edgar Luna, Yesyd Figueroa,Tanche-Larsen Per-Bjarte, Baker Hughes Drilling Fluids.

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Abstract

A severe lost circulation problem was encountered while drilling a development well in the BP Liria field in eastern Colombia. More than 18,000 bbl of OBM were lost during the well. The mud density curve for the well was established by the operator and the fluids company team as a compromise between wellbore instability and potential lost circulation that was encountered in off-set wells. The planning also considered the use of LCM materials in the formulation of the OBM and contingency plans for total lost circulation. Despite all the considerations made during the planning stage, lost circulation problems were encountered. As a consequence the pipe became stuck and the team decided to take a different approach for the sidetrack section.

A workshop was conducted by the team in order to analyze the problem and the potential solutions. The team recommended the addition of 20 lb/bbl of synthetic graphite material to the whole system and the use of down hole tools to monitor the ECD in real time, during the sidetrack interval. The application was based on lessons learned, which had been captured by the fluids company in both the UK and the GOM. The side track section was successfully drilled and the losses were reduced from 60-80 bbl/hr to an average of 10-20 bbl/hr.

The subsequent well was designed by using the same approach and no mud losses were observed in the equivalent section, which confirmed the efficiency of the new graphite product introduction.

Introduction

Several operators are drilling in difficult environments which are which are comprised of reactive clays and lower equivalent circulating density (ECD) pressure windows. The use of emulsion-based drilling fluids have been very successful for maintaining rate of penetration and wellbore stability in the reactive shale, but have increased the severity of lost-circulation situations. Industry experience has shown that lost circulation problems are typically more severe with emulsion-based drilling fluids than with water-based drilling fluids, if losses occur. A severe lost-circulation event can cost a million dollars or more from delays and fluid losses and sometimes result in loosing the well. It is clear that improved lost-circulation control capabilities can have a significant economic impact and is a key for reducing the drilling risks in such environments

Induced Losses

Induced losses result from the creation and extension of fractures during the drilling operation. Induced fractures are formed when the fluid pressure in the annulus exceeds the fracture gradient of the rock. This causes the formation to part, opening a fracture and allowing drilling fluid losses. Losses that occur during pressure surges and are often characterized by their intermittent nature and flow back as the fracture closes when the pressure is reduced.

Unlike natural losses, which first occur at the bit, induced fractures occur in the weakest formation. For a given formation, rock strength generally increases with depth so that the location of the fracture is often closer to the previous casing shoe than total depth. This attribute of induced fractures complicates the identification of the loss zone and the placement of materials designed to combat the problem. Anticipating and planning for induced losses at the design stage of a well are clearly important.

Induced fractures can take place if the mud weight selected is simply too high. Fractures can also occur when the ECD is high due to viscosity effects, when drilling or tripping too fast, or as the result temporary surge pressures due to insufficient hole cleaning. Often there is a combination of more than one of these situations.

Depending upon depth, the fractures created will either be horizontal or vertical. If the depth is around 760 meters (2,500 feet) or less, horizontal pancake fractures are usually produced because the vertical stress (overburden) is low and is less than the horizontal stresses. Lifting the entire overburden is therefore easier than parting the rock sideways. At depths over ~1,700 meters (3,500 feet), the fractures are usually vertical since the overburden now exceeds the horizontal stress.

Curing losses occurring in induced fractures can be troublesome, unless the ECD can be reduced. They are often characterized by the fact that loss rates are high when circulating, but significantly reduced or even stopped when the mud is static. This is often referred to as ballooning or breathing and can lead to backflow of fluid and LCM into the well bore as the fracture closes. Propagation pressure needed to grow the fracture is generally much lower than the initiating pressure. Consequently, losses can occur suddenly and develop rapidly to give higher loss rates[1].

Raising Fracture Pressures

Increasing the fracture gradient, and effectively increasing rock strength, could greatly reduce the likelihood of induced losses. Although there is still debate, it is fairly-well agreed that reducing losses in permeable rocks such as sandstones is easier, due to tip screen-out effects. Because the mud cake produced within the fracture quickly bridges near the fracture tip and prevents fracture propagation. The risk of induced losses in permeable rocks should therefore be considered to be generally low. In low permeability rocks such as siltstone and shale, virtually no leak-off into the matrix is possible which prevents the mud cake build-up within the fracture. Current theories suggest that the fracture gradient can still be enhanced by sealing the fracture and propping it open. In this method, the hoop stress is increased and the rock around the well bore is put into compression. This should have a strengthening effect. Another idea is that it may be possible to chemically strengthen rocks, by using resins pumped as pills. In theory these methods should allow higher mud pressures to be tolerated without losses.

Previous Work

Rock fracture and lost circulation depends on Young's Modulus, borehole size, existing flaws or fractures in the wellbore, the length and width of the fracture and the type of the drilling fluids, as well as all the other parameters involved in conventional theory.

The sealing of fractures to minimize losses has been studied in the past. A JIP[1, 2] supported by most major operators and service companies, studied the propagation and loss prevention in fractured rock. A total of 25 tests were conducted on cores in a test apparatus which fractured the rock, then evaluated the efficacy of various drilling fluid additives in inhibiting pressure communication along the fracture. The main conclusions of the study are included below:

Particle type appeared to be the most important variable for obtaining a fracture sealing response in the test apparatus. Repeated fracture sealing responses were seen in tests using graphite and thermo-cured plastic granular LCM, while calcium carbonate failed to show fracture sealing responses. Other LCM tested gave an intermediary response showing some fracture conductivity impairment. The graphite LCM showed sealing responses in a variety of core material, from high permeability Sandstone to low permeability Pierre I Shale.

Although there are some concerns with the test methodology, the key conclusions from the final report indicated that 8-12 lb/bbl of graphite should be maintained in the mud and not added as a post-fracture pill. Improved fracture sealing response was seen with 'broad' distribution of 'coarse' graphite material with significant amount of particles greater than 300 um in size. Finer graphite particles had relatively poor sealing capabilities in this test series.

Morita et al [3] describes a series of fracturing tests that evaluated borehole breakdown pressure when drilling fluid was used as the injection fluid. They observed that borehole breakdown didn't occur until the well pressure significantly exceeded the pressure which results in a tangential stress equal to the rock tensile strength. Based on these tests, a theory of fracture initiation and fracture propagation was developed. The main conclusions from the study indicated the drilling fluid acts as a good sealant for minute cracks and narrow fracture tips and lost circulation occurs when the fracture becomes unstable. This work also indicated that thermal cooling, hole inclination and pore pressure build-up affected lost circulation pressure, but did not affect it as significantly as conventional theories had predicted. The lab tests and modeling indicated the fracture width at the point where fracture pressure is sealed due to solid bridging varied between 250 and 380 um. The fracture width at the point where fracture pressure is sealed due to de-hydrated mud varies between 250 and 635 um, depending on the drilling fluid and fracture size. The borehole breakdown pressure increases as hole size is reduced. For example, reducing the hole size from 8-1/2 to 6 results in a 300 psi increase in the breakdown pressure. These match lab tests reported in SPE 28051[4] which concluded that a 115 psi increase in breakdown pressure per inch reduction in hole size could be expected.

Fuh et al [5] documented in 1992 field tests which validated the lab and model data discussed above. The paper states that the particles added to the drilling fluid should be relatively large and in a significant concentration. Also, the particles should be present in the fluid prior to fracture initiation to facilitate the screen-out mechanism. A key conclusion from the field study was an increase in the fracture propagation pressure in the range of 3-6 lb/gal.

Alternative Model for Fracture Gradients

Alberty and McLean discussed alternative theory coupled with growing evidence of its applicability. This work indicates that sands are not in general the cause of losses associated with induced fractures. Despite sandstone formations being under lower in-situ stress compared to adjacent shale layers, it is in fact the shale that are more likely to host an induced fracture responsible for large-scale mud losses 6, 7.

Most conventional theory does not recognize the “healing” property of the sands. However, it is believed that mud becomes dehydrated as it travels further into a fracture. The mud becomes immobile, hence blocking the fracture. This allows fractures to heal. Because there is physical displacement created at fractures, the displacement increases stresses in a circular pattern around the borehole. Additional increase in hydraulic pressure will create new fractures where the concentric stress is lowest. New fractures will then tip screen out creating new displacement and further raise the stress field. The theory present indicates that effectively a stress cage is created with virtually unlimited stress potential.

Field Experiences with Synthetic Graphite

Synthetic graphite was originally introduced in the UK sector of the North Sea. The product was originally designed as a solid lubricant. However, synthetic graphite has also been proven to work as an efficient well bore strengthening and lost circulation material in the UK and Norway. The increase in magnitude and frequency of down hole losses as a consequence of the pressure reduction in the reservoirs has placed development fields at risk. The addition of synthetic graphite has been a major factor in preventing down hole losses in highly depleted reservoir formations, and allowing drilling operations to continue with significantly reduced problems.

Comparative Performance

The solids particle distribution and sieve analysis of synthetic graphite is indicated in **Tables 1** and **2** and a picture of the material is shown in **Figure 1**. Note that the mean particle size (D_{50} value) is larger than 300 microns. **Table 3, 4** and **Figure 2** documents the improvement in drilling performance on North Sea wells as a consequence of the introduction of synthetic graphite in the oil based drilling fluid formulation. The continuous improvement is clear on wells D, E, F and G with the reduction in total mud losses. Increased performance is also reflected in the recorded NPT associated with those events.

Lessons learned from applications in the North Sea were a major factor for the application of synthetic graphite to overcome lost circulation problems in Colombia.

The Cusiana Recetor Field - History

The Cusiana Recetor Field is located in the Foothills of the Andean Mountains, Casanare State, Colombia.(**Figure 3**) This is the largest discovery in the country in the last 10 Years**.** Drilling in the Cusiana field by Ecopetrol - BP, with BP as the operator, began in October 1987 with the spud of Cusiana 1. Since that time over one hundred wells have been drilled and completed. Drilling in the foot hills proved to be most challenging with numerous problems such as lost circulation, water flows and cavings. These problems resulted in hole enlargement, stuck pipe, pack offs, twist offs, bacteria degradation of mud, carbonate contamination, and tight holes. From the experience gained from drilling over one hundred wells and numerous studies, many of the problems are now understood and have resulted in a reduction in NPT.

The major drilling difficulties in foot hills have been caused by the tectonic stresses on the formations being drilled, resulting in a large amount of cavings while drilling and reaming. The cavings cause hole enlargement, pack offs and stuck pipe incidences. Early information indicated that the Carbonera shale is micro fractured and the initial approach to control the cavings was to increase mud density and to use asphalts and Gilsonite as bridging materials. Unfortunately, the result of increasing the mud density caused severe lost circulation, both with water-based and oil-based muds. Currently a recommended mud weight curve is followed with slight density increases with increasing depth. Asphalt is now supplemented with graded calcium carbonate for bridging the micro fractures.

Lost circulation or seepage normally occurs in the Carbonera C5, C7, C8, or Mirador formations. It is thought that most of these lost fluid occurrences are due to natural fractures in the formations and are quickly sealed with lost circulation pills. In earlier wells, with high mud densities, mud losses ranged in the thousands of barrels. Since mud densities have been reduced, the losses have been reduced to a few hundred barrels per well.

Packing off of the drill string occurs when the wellbore is unstable and the rheological properties of the drilling fluid are not adequate to transport or suspend the larger size cavings. Recent practices of increased awareness, higher low shear rate viscosities, and higher pump rates have reduced the number of pack off incidents.

Reaming into and out of the wells has constituted many hours of non-productive time. During the early wells, the wellbore instability caused by the long exposure time, excessive mud densities, and lack of bridging materials caused the operator to spend more time reaming, rather than drilling. Currently reaming is only necessary when directional problems requires trajectory corrections

Liria Well Planning

Lost circulation was considered as a potential wellbore problem during the planning stage, due to the number of incidents observed in close offset wells. As a consequence the mud density curve was designed as a compromise between lost circulation and wellbore stability. Preventive measures and contingency plans were considered in the Basis of Design.

Despite the considerations made during the planning phase, severe lost circulation problems were observed while drilling the 17-1/2" hole section. A total of 18,292 bbls of oil based mud were lost to the formation and the pipe became stuck.

Due to the severity of the problems observed in the previous wells in this area, a task group was set up to look for preventing rather than curing, the problem. As a part of the study, case histories and documented field experience from previous applications of synthetic graphite in the UK and Norwegian part of the North Sea were investigated.

During the planning of the Liria well, various drilling fluids options were discussed, including drilling with pressures above the minimum horizontal stress. This included the review of data which examined the possibility of drilling above the fracture propagation pressure (FPP) and recommendations regarding the additive type and treatment amounts.

The following guidelines were put into place.

- Graphite additions would be made to the oil-based mud.
- The particle size would be relatively coarse, with a mean size of approximately 300 microns.
- Dependant on the shaker screen sizes, significant amounts of the graphite would be stripped out of the mud when processed through the solids control equipment. The coarse graphite particles were considered important to the potential success of the fracture sealing response of the fluid, hence active maintenance of the graphite would be made at the rig-site, similar to maintenance of coarse carbonate particles when drilling high permeability sands.
- The concentration in the fluid would be at least 20 lb/bbl. Although the concentrations in the JIP tests were 50% of this, the scale of the lab tests versus field cases was difficult to quantify. A higher concentration was recommended for field use until a better indication of the necessary active concentrations required was determined.
- Lab tests were used to evaluate whether this level of additions would be detrimental to the fluid rheology.
- The graphite would be incorporated into the whole system in a preventative measure, rather than used as a pill treatment once losses were experienced.

In terms of increasing the ECD window, two references discussed previously illustrated that reduced hole sizes with respect to well bore will potentially have higher breakdown pressures and this approach would be applied if possible.

Laboratory Testing

A series of laboratory tests were conducted to determine the effect of synthetic graphite concentration of 1.0 to 20.0 lb/bbl in an oil-based drilling fluid formulation. Testing was conducted on 90 micron Aloxite disks using Sand Pack Permeameter, to determine the relative sealing ability of various particles and concentrations. The results are reported as Permeability Plugging Test (PPT) and results are given in **Table 5** and **Figure 4.** Schematics of the apparatus used for the testing are shown in **Figure 5**.

Synthetic Graphite Additions

A premix of 400 bbl oil-based mud containing 20 lb/bbl of synthetic graphite was added to the active system to ensure a homogeneous concentration of synthetic graphite. The Fluids engineers closely monitored the fluid viscosities and adjusted the concentration as needed based upon drilling parameters. A premix volume to maintain 2.0 lb/bbl in the active system was utilized. The additions were made after the drill-out of cement, and when more than 40% formation solids were observed in the shaker samples.

The same procedure was used to increase the synthetic graphite concentration to 5 lb/bbl as drilling continued. Lab results indicated that the addition of additional surfactants at a 0.2 to 0.5 lb/bbl concentration was necessary to keep the fluid viscosity properties within specifications.

The final synthetic graphite concentration of 15 to 20 lb/bbl was achieved by adding an additional 1 lb/bbl material per 300-400 ft drilled.

Scalping shakers were set-up with 12-20 mesh screens and Flow-Line Cleaners with 50-84 screens for maintaining the synthetic graphite in the active system. This was determined to be a critical approach for the application as determined by the review of lessons learned from previous experiences, where a significant loss of synthetic graphite over the shakers was observed.

LCM pills of 20 bbl, containing; coarse asphalt, mica, coarse calcium carbonate and Kwik Seal (total 60lb/bbl) was pumped before entering the lost circulation zones previously identified during the planning phase. A total volume of 400 bbl LCM pill was maintained as a contingency during the interval.

Results

On the Liria well synthetic graphite has been added at concentrations from 15 to 20 lb/bbl. Additions made after drilling out the cement plug have proved beneficial. Although LOTs have not been conducted on all the wells, drilling fluid losses to the Guayabo, Leon and Carbonera C-1 below the casing shoe were significantly reduced compared to the offset wells. The average mud losses were reduced from 40-50 bbl/hour to 10 bbl/hour in the sidetrack hole section. The losses increased to 20 bbl/hour averages in the lower C-2, C-3 and C-4 formations that were not drilled in the original hole and decreased to an average of 10 bbl/hour in the Carbonera C-5. **(Figure 6)**

The continued use of synthetic graphite in the 10-5/8" section where the entry pressure into the C-5 has been lower, has proven to be successful and no losses were experienced while drilling the section. **Table 6** gives typical fluid properties in both hole sections.

Conclusions

- The drilling fluid losses have been reduced by 82%; 2,226 bbls compared to 18,292 bbls in the original hole by using synthetic graphite in the oil based mud.
- The volumes of LCM pills were also reduced by 83% using this approach. Only 350 bbl were pumped, as compared with 2,575 bbl on the offset.
- No wellbore instability problems were observed while drilling the new hole section.
- The use of pressure measurement tools for ECD monitoring was a key factor for controlling mud losses. Mud losses increased in C-4 formation correlated with ECD increases.
- The 12-1/4" hole section was drilled using higher than expected mud density due to wellbore instability concerns. The synthetic graphite helped prevent lost circulation in the C-5 formation.
- The higher losses rate observed in C-2 and C-4 shale sections, as compared with C-1 and C-5 sand formations, agreed with Alberty & McLean that more than likely shale formations were considered the site of large scale mud losses.
- No adverse effects on rheological properties were observed with additions of synthetic graphite.
- Control of screen mesh size, flow line temperature and additions made after drilling out cement minimized losses of synthetic graphite.
- The performance index of base fluid by using 20 lb/bbl of synthetic graphite was improved by 80% as per indicated by sand pack permeameter results.

Acknowledgments

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Nomenclature

LCM = *lost circulation material*
NPT = *non productive time*
JIP = *Joint Industry Project*
GOM = *Gulf Of Mexico*
pptf = *pounds per thousand foot*
ɥm = *microns*
OBM = *oil based mud*
bbl = *barrel*
WBM = *water base mud*
lb/bbl = *pounds per barrel*
lb/gal = *pounds per gallon*
FPP = *fracture propagation pressure*
CRI = *cuttings re-injection*
LOT = *leak off test*
ECD = *equivalent circulating density*
TD = *total depth*
TVD =*true vertical depth*
EMW = *equivalent mud weight*
PWD = *pressure while drilling*

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Table 1: Particle Size Distribution of Synthetic Graphite

D-10	D-50	D-90
156ųm	341ųm	485ųm

Table 2: Synthetic Graphite Sieve Analysis

Mesh Size	% Retained
40	27
50	22
60	12
80	19

Table 3: UK Wells drilled in 2002 prior to the use of Synthetic Graphite

Well	Mud Lost (bbl)	Reached TD w/o losses?
A	6,397	No
B	18,794	No
C	6,497	No

Table 4: UK Wells drilled in 2002/2003 with Synthetic Graphite

Well	Mud Lost (bbl)	Reached TD w/o losses?
D	1,924	Yes
E	2,024	Yes
F	0	Yes
G	1,432	Yes

Table 5: Effect of Synthetic Graphite on fluid properties Liria Well

Property	Base 9.5 lb/gal Oil Base Mud	Base+ 1lb/bbl Synthetic Graphite	Base+ 5 lb/bbl Synthetic Graphite	Base+ 10 lb/bbl Synthetic Graphite	Base+ 15 lb/bbl Synthetic Graphite	Base+ 20 lb/bbl Synthetic Graphite
Fluid Properties 120° F						
Plastic viscosity, cp	36	37	36	37	42	44
Yield point, lb/100 sq ft	26	30	27	26	32	34
10-sec gel, lb/100 sq ft	14	16	16	16	16	19
10-min gel, lb/100 sq ft	33	33	38	38	32	39
PPT, 90 microns disk,1000 psi, 250° F						
Spurt Loss, cc	18	12	5.2	4.0	3.8	3.5
Total Volume, cc	20	14.6	7.8	6.2	5.2	4.2
PPT, cc	22	17.2	10.4	8.4	6.6	4.9
Sand Pack, Carbolita 16/20						
% Return Permeability	44	37	40	43	54	56
Filtrate, cc	NC	NC	60	58	40	35
Performance Index	**100**	**78.18**	**47.27**	**38.18**	**30.00**	**22.27**

Note: Performance Index is mathematically derived by dividing PPT by PPT of Base fluid formulation. The lower the index, denoting the higher change, the better the performance.

Table 6: Mud Losses Liria Foothills Well

Depth, ft	Mud Density, lb/gal	Max Mud Losses Rate bbl/hour	Average Mud Losses Rate bbl/hour
3,686	9.5	45	32
4,467	9.5-9.7	20	16
5,102	9.7	20	15
5,312	9.7 – 9.8	20	15
5,901	9.9	5	5
6,145	9.9	45	32
6,259	9.9	120	40
6,400	10.1	120	40
7,000	10.2	336	40
7,157	10.0	234	65
7,301	10.0	280	90
7,565	10.0	190	150

Table 7: Typical Fluid Properties with Synthetic Graphite

Interval	14 3/4"	10 5/8"
Fluid Type	Oil Base Mud	Oil Base Mud
Interval length, feet	6,353	4,113
Dilution rate, bbl/foot	1.74	2.08
Fluid Formulation		
Primary Emulsifier, lb/bbl	2.3	5.2
Oil Wetting Agent, lb/bbl	2.9	3.7
Fluids Control Agent, lb/bbl	7.7	6.9
CaCl2, lb/bbl	4.1	3.6
Gilsonite, lb/bbl	9.2	14.5
Calcium carbonate, lb/bbl	47.9	60
Organophilic Clay, lb/bbl	8.7	6.8
Synthetic Graphite	18	19
Coarse Gilsonite, lb/bbl	3.9	3.2
Density, lb/gal	9.7	13.5
Plastic viscosity, cp	38	54
Yield point, lb/100 sq ft	30	32
Gels, 10-sec/10-min/30-min lb/100 sq ft	20/30/35	25/37/43
HTHP Filtrate, ml/30 min	2.5	2.2
Salinity	64K	64K
LGS, vol %	2.64	8.7
Electrical Stability, volts	1,220	1,247

Figure 1: Synthetic Graphite

Figure 2: Mud Losses after Synthetic Graphite –North Sea

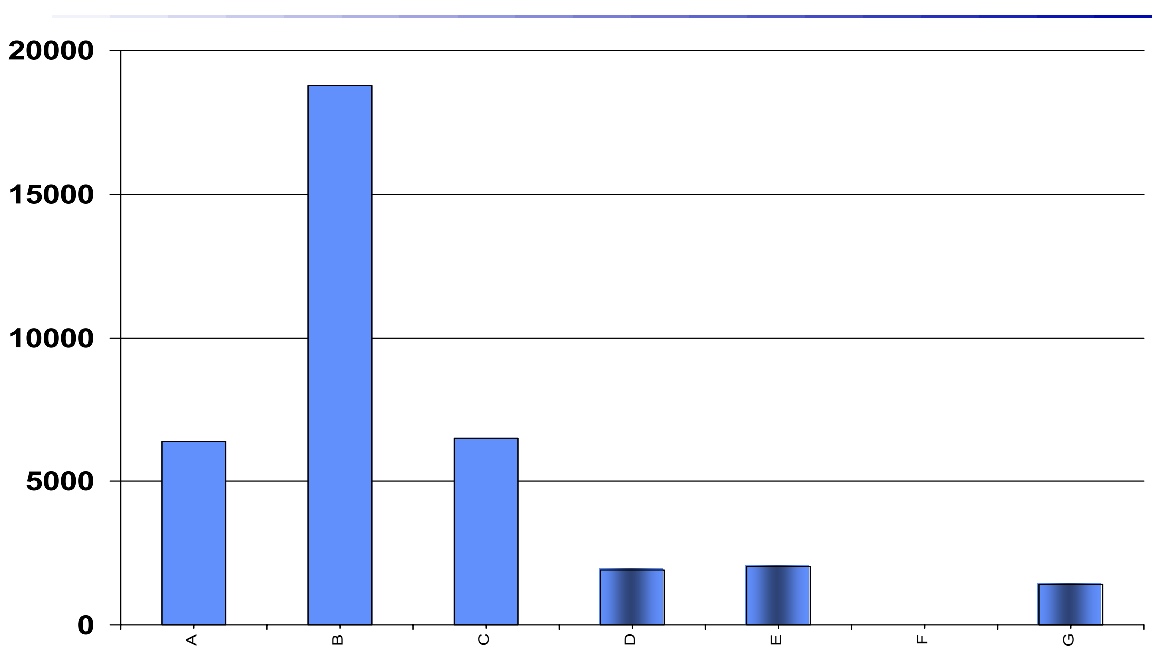

Figure 3: Location of Cusiana- Recetor Field

Figure 4: Effect of Synthetic Graphite on PPA Values

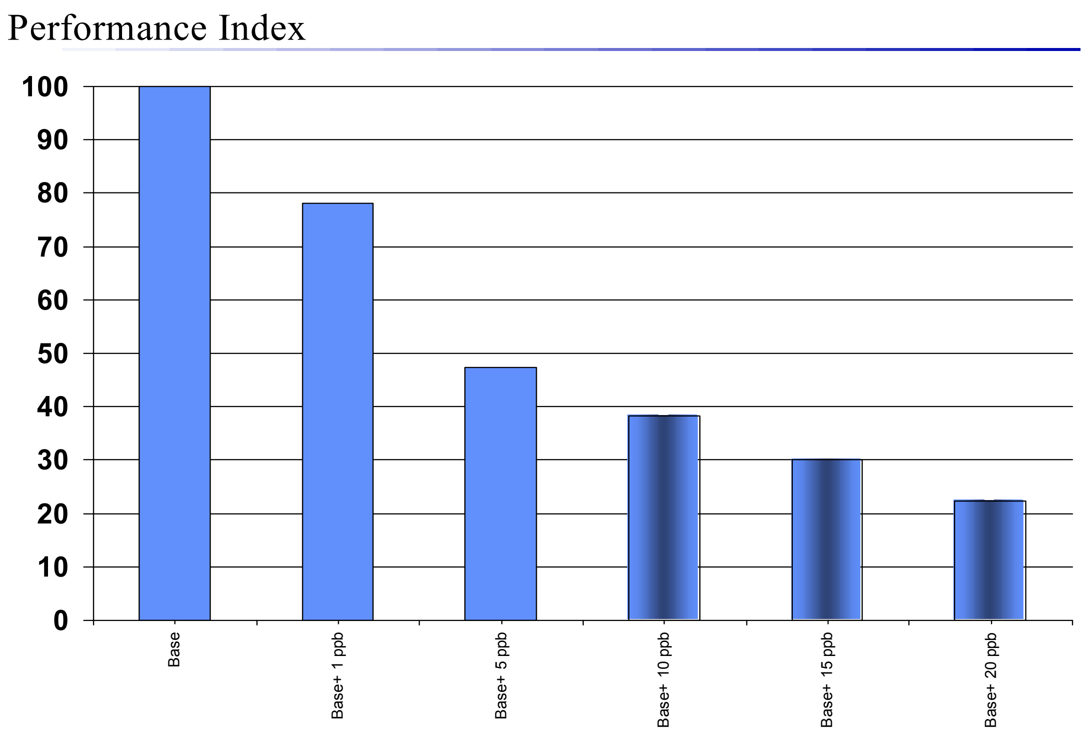

Figure 5: Sand Pack Schematics

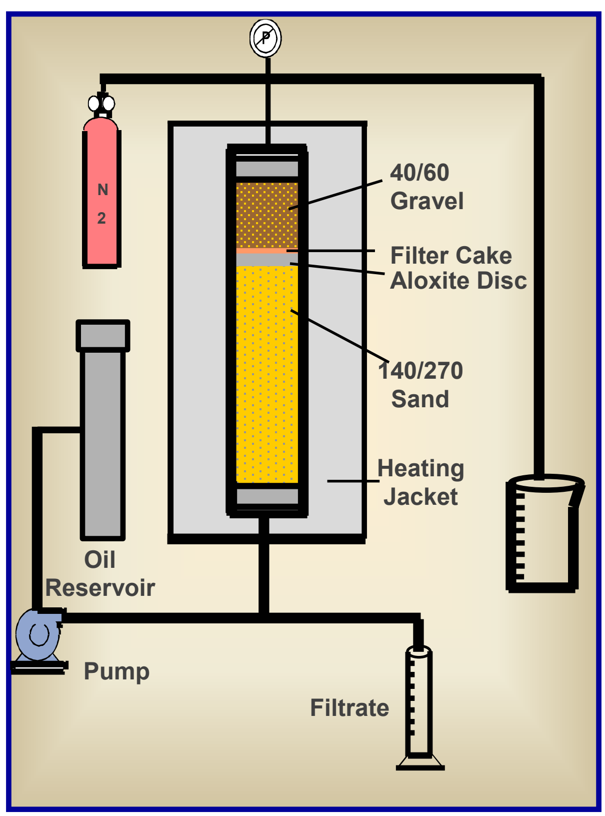

Figure 6: Mud Losses , ECD and Synthetic Graphite Concentration Liria Well