WIERTNICTWO NAFTA GAZ • TOM 23/1 • 2006

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A NEW METHODOLOGY THAT SURPASSES CURRENT BRIDGING THEORIES TO EFFICIENTLY SEAL A VARIED PORE THROAT DISTRIBUTION AS FOUND IN NATURAL RESERVOIR FORMATIONS

1. INTRODUCTION

The challenge for those involved in the design of non-damaging drill-in fluids is to effectively minimize formation damage, especially in open-hole completion applications. Formation damage may be evaluated using a number of laboratory techniques. One useful method, which is summarized for brevity, measures the initial oil or gas permeability of a natural core or other porous medium. Later, after exposing it to a drill-in fluid that is used to deposit a filter cake for a given period of time, the final permeability is measured allowing one to calculate the regained permeability.

Other methods use static or dynamic filtration tests on a core face or ceramic disc to measure the spurt loss and total filtration rates. These tests provide simple data with regard to the effectiveness of the fluids invasion control capabilities. Another common parameter to measure a reservoir fluid damage potential is the filter cake ift-off pressure requirement. This value is important especially in low pressure reservoirs where the filter cake quality determines reservoir ability to remove internal and external cake deposition with minimal flow initiations pressures.

Based on the need to design fluids that retain a reservoir permeability and controls filtrate and solids invasion as well as low cake lift-off pressures, this paper focuses on pore throat size distribution of the formation and the particles size distribution of the drill-in fluid to achieve these results in the field.

Addressing the issue of formation impairment, or its prevention, as related to sized bridging particles is directly related several damaging mechanisms. For example, excessive filtrate invasion can directly promote relative permeability reductions by blocking and/or

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plugging the pore spaces. It has been demonstrated that permeability loss is directly related to high cake lift-off pressure requirements. High filtration rates caused by ineffective bridging promote the deposition of thicker and harder to remove internal and external filter cakes [1]. In addition, filtrate invasion, especially water-base filtrates containing hydrated polymer, will ultimately block and/or reduce the flow of hydrocarbon [2, 3, 4]. Although damage from filtrate and hydrated polymer invasion is never totally eliminated, improving the particle size distribution in a drill-in fluid design that is based on the full spread of spread of pore diameters will minimize that damage.

2. BRIDGING THEORY REVIEW

One of the early advances in reservoir bridging and one that is still in use today was proposed by Abrams in 1977 [5]. Abrams suggested that both size and concentration of bridging particles was required to minimize the depth of an internal filter cake. Specifically, the particle size of the bridging material should be at least equal to or greater than one-third of the medium pore openings of the reservoir rock. Secondly, the concentration of the sized particles should be in abundance of at least 5% by volume of the solids in the final mud composition, including drill solids. These guidelines are frequently used in the field today when little is known about the pore size distribution of a particular reservoir. In these cases the fluid design utilized a wide range of particles in an attempt provide a wide range of bridging capabilities [1].

An improvement to Abrams guidelines is the practice maintaining a low concentration of drill solids [6]. Tests in this author laboratory have also demonstrated the negative effect of drill solids on a fluid ability to control filtrate invasion under dynamic conditions, an indication of poor bridging efficiency. The dynamic filtration rates, Q_o, shown for three fluids (Fig. 1) are plotted against time. All three fluids were tested on 5, 20, 35 and 60 μm ceramic discs.

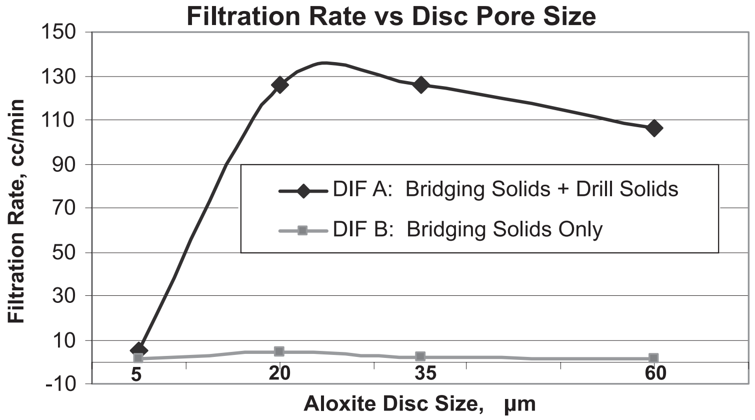

Fig. 1. Effect of drill solids/bridging solids relationship

The basic design for each fluid was identical; however, Fluids A contained 21 lb/bbl (2.4% v/v) Rev Dust and 25 lb/bbl graded calcium carbonate respectively. Fluid B had only graded calcium carbonate. As can be easily seen, the rates of filtration for fluids 2 and 5 on all the ceramic disc sizes were significantly higher than Fluid B which had low filtration rates. It can be inferred that the thicker filter cakes of Fluid A was directly be due to the loss of fluid loss control and solids invasion.

Although drill-solids will always be present in drill-in fluids, the data suggests that the concentration should be held to a minimum in field applications to minimize filtrate invasion. Testing of a large number of fluid formulations on various disc sizes indicates that bridging solids should be at least 75 0% of the total solids fraction in a drill-in fluid to maximize bridging efficiency and minimize damage due to invasion.

The Ideal Packing Theory (IPT) represents a relatively new method to improving bridging efficiency for drilling fluids [7]. This theory (rule) states that ideal packing occurs when the percent of cumulative volume versus the square root of the particle diameter forms a straight line [8].

The IPT approach is broadly based on an estimation of the median pore size estimated from permeability by taking the square root of the permeability (in mille Darcys) [7]. This would be accurate if the size distribution of pore throats in a reservoir were linear. In practice this linear relationship does not exist, and in a reservoir the most common pore throat diameter will not be the middle of the size range. The IPT approach is applicable for uniform pore throat distributions but as most reservoirs do not fit this description another model is required to provide a more efficient bridge and therefore a reduction in fluid loss into the reservoir.

When studying pore throat size distributions of reservoir cores it was realized that a new methodology would be required if we were to efficiently control fluid loss in naturally occurring formations. An accurate description of the pore throat description that is found in a reservoir can be obtained by analyzing mercury injection data. This can be obtained during the same process that is used to measure a core permeability. By utilizing this data, a more efficient method of bridging control was devised, tested and verified in the field.

3. NEW BRIDGING METHODOLOGY

A large proportion of the production flow from a reservoir will come from the largest pore throats, thus these pores must not be ignored. Also a considerable number of pore throats may be very small in comparison to the median size (D50). Essentially, when the particles are selected for the large, medium and a few of the smaller pores, the net result is a particle size distribution that does a fairly efficient job of sealing all reservoir pores and most of the void spaces in the filter cake medium itself. In other words, close packing is a collective problem, utilizing the symmetry of wide range of particles to initiate cake building.

Another way to visualize the need for a wide range of particle sizes for initiating ideal packing is to observe the loose packing of spheres as shown in Figure 2. Here we can clearly see that the uniform spheres are as tightly packed as physically possible. To create a jamming effect (tight pack), an abundance of smaller particles or particles of different shapes would be required to satisfy the interparticle gaps. Without the gaps filled, filtrate, polymer and small particle invasion would result.

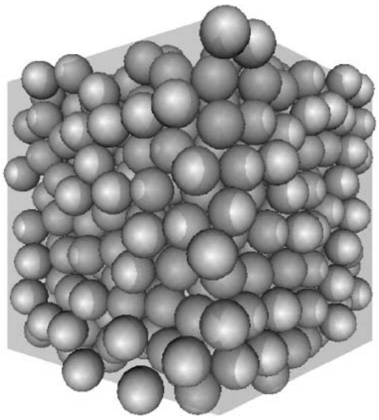

Fig. 2. Packing of Similar Spheres with Gaps

It is desirable to select a particle size distribution that will quickly bridge the largest pore openings, the medium pore size opening and a smaller pore size fraction. These targets fractions are generally selected based on the D90, D50 and D10 of the reservoir pore throat distribution.

To exceed the bridging efficiency gained by using the IPT method, it was assumed that matching more target fractions might be necessary. A series of laboratory filtration and disc-sandpack permeability tests were performed to demonstrate that matching the PSD blends with additional targets would result in reduced filtration rates and improved return permeability results. The additional target fractions chosen included the D75 and D25. Using all five targets, the D90, D75, D50, D25 and D10, has resulted in what we have named, he Vickers Method.

The following criteria (Vickers criteria) for the bridging blend should meet the following standards to achieve to minimal fluid loss into a reservoir.

- D90 = largest pore throat;
- D75 < 2/3 pore throat;
- D50 +/– 1/3 of the mean pore throat;
- D25 1/7 of the mean pore throat;
- D10 > smallest pore throat.

This method is based in part on the laboratory studies described below and has been a critical tool for designing improved drill-in fluids, especially when adequate pore size data are known. The Table 1 shows the efficiency of three methodologies. The fluids were also tested on a sandpack permeameter (Fig. 3) to measure the return permeametry and lift off pressure. This test measures the ability of the filter cake to form on the surface of the filter medium and not to build any internal cake form deep invasion of small particles.

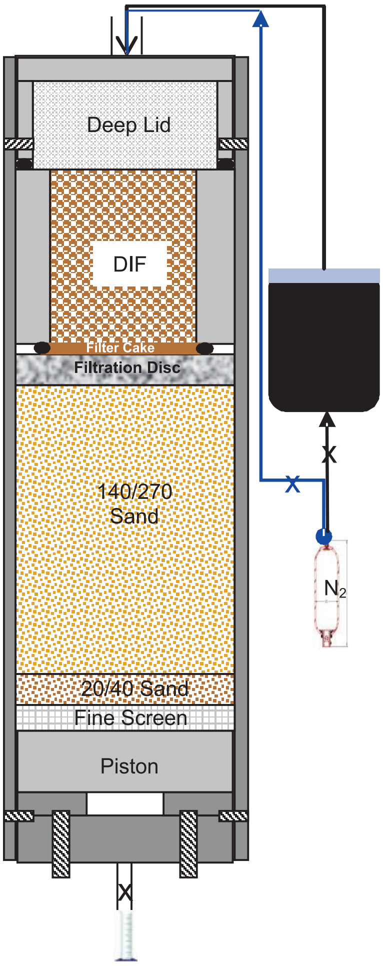

Fig. 3. Disc Sandpack Permeameter (Schematic)

Table 1

PPA Filtration and Return Permeability

PPA Disc Size – 5 µm				
Bridging Theory	Vickers	IPT-1*	IPT-2*	Abrams
Spurt Loss, cc	4.4	8	5.6	6
30 min Filtration, cc	21	22	26	30
Lift-off Pressure, psi	1.2	2.8	2.4	2.6
% Return Permeability	93.8	49.5	78.6	61.5

Table 1 cd.

PPA Disc Size – 20 μm				
Bridging Theory	Vickers	IPT-1	IPT-2	Abrams
Spurt Loss, cc	2.6	19.2	14	3.6
30 min Filtration, cc	20	42	33	23
Lift-off Pressure, psi	0.9	4.4	2.0	5.0
% Return Permeability	85.7	69.5	74.2	80.9
PPA Disc Size – 60 μm				
Bridging Theory	Vickers	IPT-1	IPT-2	Abrams
Spurt Loss, cc	4.4	15	3.6	2.4
30 min Filtration, cc	20.8	31	20	19
Lift-off Pressure, psi	0.6	2.6	1.8	1.4
% Return Permeability	86.2	78.1	91.5	93.5
Average Values Over Entire Pore Throat Range				
Lift-off Pressure, psi	0.9	3.3	2.1	3.0
% Return Permeability	88.5	65.6	81.4	78.6

* IPT-1 contains 30 lb/bbl and IPT-2 contains 50 lb/bbl

4. BRIDGING SOLIDS EFFICIENCY AND SANDPACK PERMEAMETRY TESTING

Separate samples of a typical WBM DIF, containing the calculated bridging solids concentration and particle size distribution as recommended by each of the bridging theories, were mixed in the laboratory. To calculate the bridging distribution required, it was assumed that the pore throat distribution in the test would simulate a reservoir with a D90 of 60 micron, a D50 of 20 micron and a D10 of 5 micron. This pore throat distribution size is typical range found in sandstone reservoirs.

Each of the fluids were tested for filtrate loss and bridging efficiency on a range of ceramic discs with pore throat sizes corresponding to the design criteria. The testing was conducted using a typical HPHT filtration apparatus modified to accept a ceramic disc as the filtration medium. Both spurt loss (after 30 seconds) and fluid loss after 30 minutes through each of the discs were measured.

The results of these tests clearly showed the improved spurt and total fluid loss values exhibited by the fluid containing the solids calculated by the Vickers selection method. The results clearly demonstrate the need for a bridging solids concentration greater than 30 lb/bbl as recommended by Dick [7]. The laboratory evaluation and previous field experience has shown that a concentration of 50 lb/bbl is more efficient at controlling filtrate loss. As pore throat size increase towards the D90 values the Abrams method becomes more efficient. The IPT selection method is the least effective across the entire range of pore throat sizes.

To evaluate each of the fluids efficiency in forming an external filter cake and their formation damage potential a Sandpack Permeametry on each of the selected disc sizes was conducted (Fig. 3).

The initial Permeability of the each Sandpack was established at room temperature using a clean mineral oil as the reservoir fluid. The test fluid was then exposed to the selected ceramic disc for 1 hour at 200°F and 500 psig overbalance. Filtrate loss was allowed through the disc. The final permeability was conducted in the same manner as the initial. A return permeability is calculated from the ratio between the initial and final permeabilities. The pressure required to lift the filtercake and initiate flow is also measured.

From the results the Vickers selection method demonstrated the lowest filter cake lift off pressure and the highest return permeability values across the pore throat range (Tab. 1). The study shows a relationship between low fluid loss and resulting high return permeability. Therefore in order to maintain maximum productivity it is essential that spurt and overall fluid loss are minimised.

4.1. Laboratory and Field Case 1

This study was based on data obtained from the field Schehalion in the North Atlantic, West of Shetland, operated by BP. The reservoir engineers required a fluid design that would result in a production rate of at least 6 mbopd. From mercury injection data on field core, calculations indicated that approximately 90% of the pore throats were < 30 μm, 50% were < 20 μm, and the smallest 10% were < 2 μm.

Various DIF designs were evaluated by measuring their fluid loss characteristics on two aloxite disc sizes. Aloxite discs are purchased with fixed pore openings and the nearest matches to the BP reservoir were 20 and 35 μm rated discs. From these results (Figs 4, 5 and 6), it was obvious that one of the formulations was giving very good filtration control.

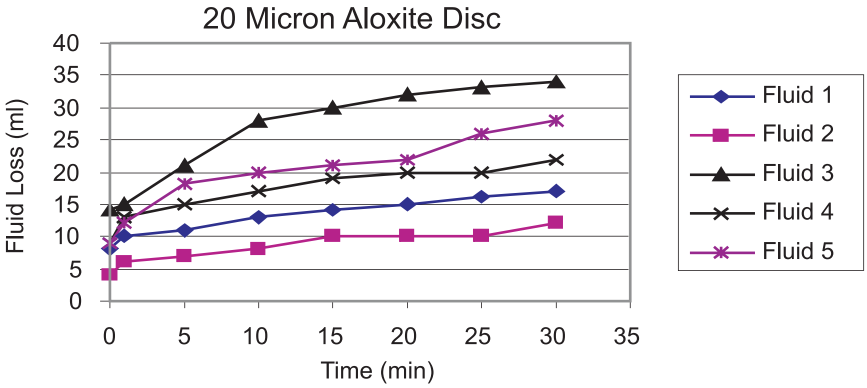

Fig. 4. Fluid loss on a 20 μm disc. Fluid 2 used the Vickers Bridging Method

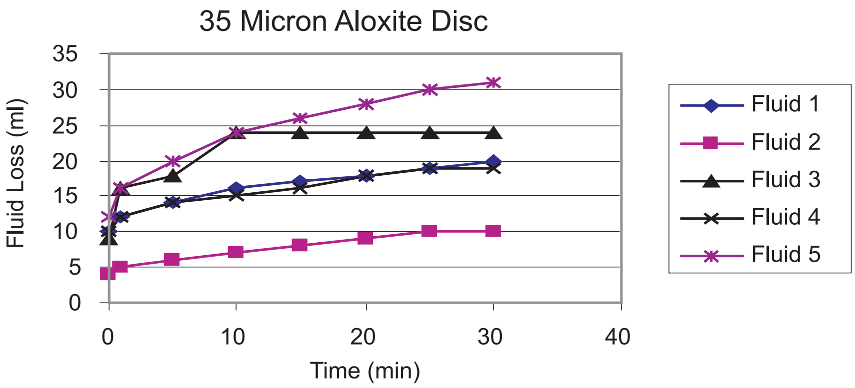

Fig. 5. Fluid loss on a 35 mm disc. Fluid 2 used the Vickers Bridging Method

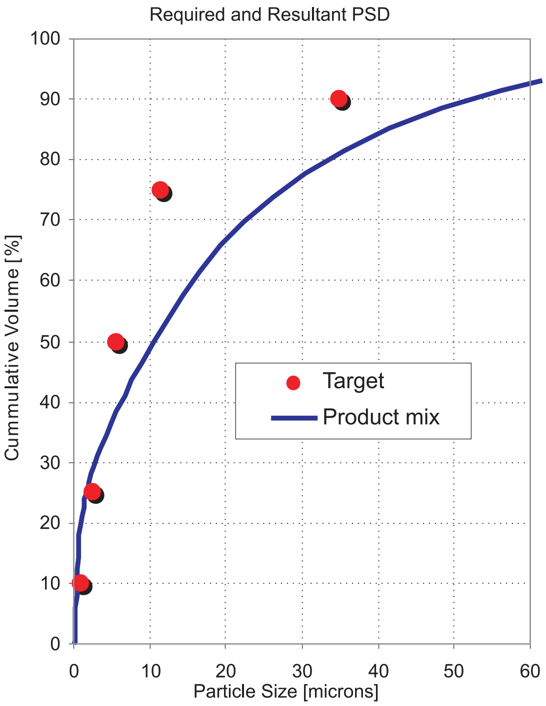

Fig. 6. Vickers Method PSD Fit (Case 1)

This formulation was selected for a full return permeability test on actual reservoir core that had been supplied by the operator. Formation damage testing resulted in greater than 90% return permeability. Samples of the proposed formulation were sent to BP for verification and after further testing, it was concluded that this fluid design would not result in unacceptable loss of permeability.

The DIF was built and run on the rig as specified. Real time testing of the bridging efficiency of the fluid was carried out on the rig by using the Particle Pore Throat Tester apparatus. This is a modified HPHT fluid loss cell. Instead of filter paper in the cell, an aloxite disc is used instead. If the filtrate loss increases it should be assumed that more bridging material is required as it will have probably been stripped out at the shakers or ground down. Verification of this can also be achieved by using particle size analysis from a using laser particle size analyzer.

The formulation used on this well consisted of the following components:

- drill water0.259 bbls;
- NaCl brine 0.121 bbls;
- KCl 0.481 bbls;
- viscosifing polymer 1 lb/bbl;
- fliltrate control polymer 6 lb/bbl;
- calcium carbonate A25 lb/bbl;
- calcium carbonate B25 lb/bbl;
- gylcol 3%;
- lubricant 3%;
- pH buffer1 lb/bbl.

The reservoir was drilled without problems and is currently producing 12.5 mbopd on a 50% choke, more than two times BP requirement.

4.2. Laboratory and Field Case 2

This study involved a 10.3 lb/gal water-based calcium carbonate drill-in fluid seeking approval for a North Sea gravel pack application. Because the formulation had to be right when tested by the independent laboratory, a series of filtration tests with DIF formulations having varied calcium carbonate blends were conducted on a series of aloxite discs. The disc sizes, 5, 10, 20, 35 and 60 μm, were chosen to simulate the varied pore throat sizes in the reservoir. The Vickers Method approach of optimizing the bridging blend for multiple target pore size openings was utilised. Furthermore, the best polymer and brine compositions were pre-qualified and remained the same for all formulation testing. Pre-testing on the aloxite discs provided our laboratory technicians solid data to formulate and submit a fluid formulation to the operator laboratory of choice.

Figures 7, 8, and 9 show filtration data for six drill-in fluid designs tested on the five aloxite discs. Figure 10 is a graph of the PSD versus the Vickers Targets. The goal was to formulate a single design having a calcium carbonate blend that best matched all five discs. As can be seen from the data on each graph, the formulation with Blend B had the lowest spurt, lowest total filtration and lowest cumulative spurt total filtration values. Thus, the Blend B fluid was selected for outside laboratory permeability testing.

Careful selection of bridging particles to meet the multi-target ranges is very critical when the core flood testing program is designed to challenge even the best fluid designs.

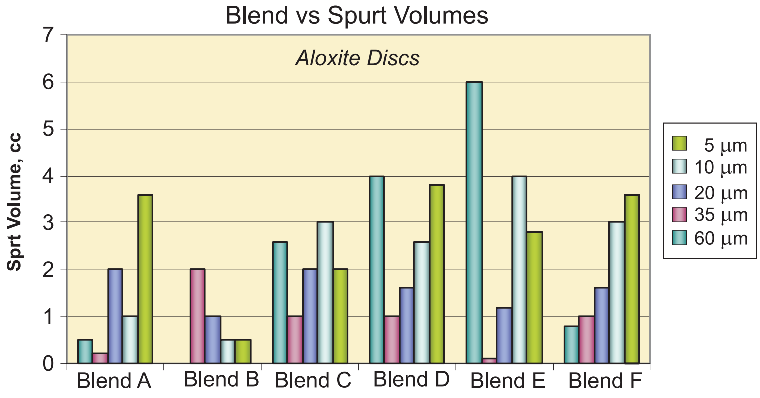

Fig. 7. Bridging Pre-design Study (1) Case 2

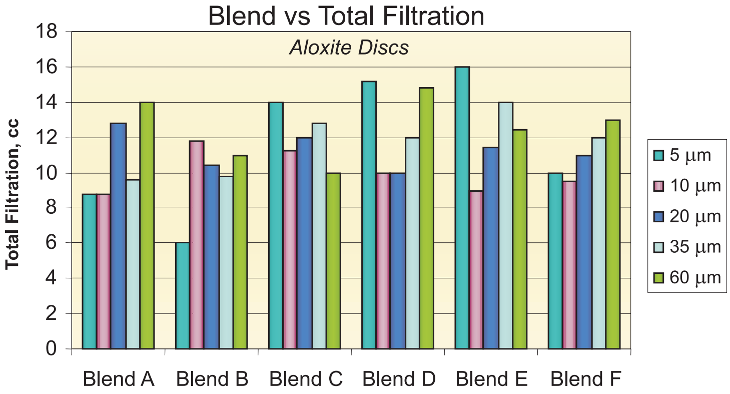

Fig. 8. Bridging Pre-design Study (2) Case 2

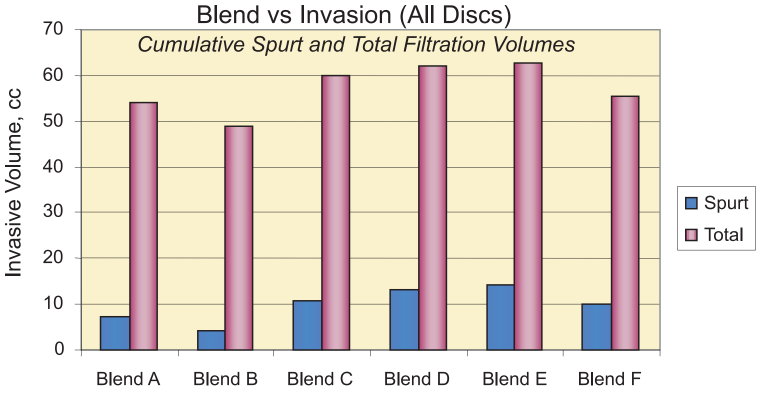

Fig. 9. Bridging Pre-design Study (3) Case 2

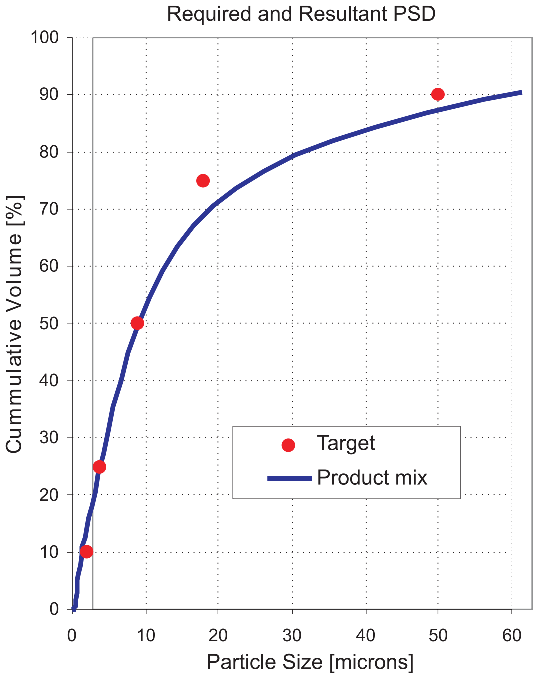

Fig. 10. Vickers Method PSD Fit (Case 2)

The test program for this project included the following fluid exposure steps to determine the return permeability:

1. 48-hr dynamic mud-off;
2. 48-hr static mud-off;
3. 10-min dynamic mud-off;
4. 10-min dynamic brine displacement;
5. 24-hr static brine soak (800 psi overbalance);
6. Carrier fluid saturated Proppant and screen;
7. 7-day static soak with carrier fluid w/ breaker.

The 60% return permeability to humidified N_2 gas only required 4.5 psi drawdown. Further testing of different fluids, including those from different fluid providers could not surpass this result. Typical results frequently fall below 40% return permeability unless a fluid is designed with a calcium carbonate blend that satisfies the ideal packing conditions of multiple targets as demanded by the Vickers Method. Field results of this case study are not available at the time of this printing.

4.3. Laboratory and Field Case

This study was for the Farragon project for BP in the North Sea that utilized OBM to drill the reservoir section but was then gravel packed using brine carrier and completion fluids. Because the payzone was to be drilled with an OBM and because pores invasion would be almost entirely oil, it was critical that any further invasion by aqueous fluids during the completion phase be minimized to reduce any damage from immiscible fluids. Due to a scarcity of actual reservoir core, Berea Sandstone of similar physical properties to the reservoir was used in the permeametery tests. Again the pore throat data was studied, the diameters and proportional distribution information was fed into an in-house software package that will model the Vickers Method for prediction of bridging size selection. The pore distribution for this project showed a D90 of 35 micron, D50 of 17 micron and a D10 of 2 micron. This software prediction showed that a blend of two different sized Calcium Carbonates was required, and this information was used in the fluids design. The plot of the bridging size prediction using the Vickers method can be seen in Figure 9. Further evaluation tests were done on Aloxite discs to check the bridging efficiency and then the DIF was used in the return permeameter using Brea sandstone. After both OBM and WBM had been flushed across the core face a return perm of 74% was measured.

The fluid formulations that had passed the lab tests were then utilized in the field. The reservoir was drilled and gravel packed as planned. Two wells were drilled on this project and both wells are collectively producing 22,000 bopd, 2,000 bopd more that expected by BP despite production while on choke.

4.4. Laboratory and Field Case 4

This study involved an 11.2 lb/gal synthetic-based drill-in fluid (SB DIF) scheduled for a deepwater GoM gravel pack application and formulated with a used mud that had been cut back to 8.3 lb/gal density (Tab. 2). This fluid was reformulated for reservoir permeabilities ranging from ~700 mD down to zero mD. The bridging blend included barite required for density and the best calcium carbonate blend to satisfy the 5 target defined by the Vickers Method and shown in Tables 3 and 4. To confirm the PSD blend, three Berea core samples were selected, one in the 700 00 mD range, 200 00 mD range and one in the 50 00 mD range.

At an independent laboratory selected by the operator, on three Berea core samples, the SB DIF filter cake was deposited dynamically for 4 hours followed by sixteen hours of static deposition and an additional two hours of dynamic deposition. The drilling fluid was displaced with a push pill. The push pill was followed by a WB DIF flush and a static soak for 4 hours. Finally, 11.2 lb/gal NaBr completion brine displaced the soak fluid. Flow was then initiated in the production direction with LVT-200 mineral oil.

Because the return permeability results were for each core were high and the dynamic filtration results very low, it was concluded that bridging blend satisfied each of the Vickers targets, including very desirable intergranular gap packing in the external filter cake.

From the laboratory, the design was tested in the field. Results from this application are pending.

Table 2

SB DIF Formulation and Properties (Case 4)

Composition	
8.3 lb/gal Base Mud, bbl	0.82
Water, bbl	0.099
$CaCl_2$, lb	9.27
Emulsifier, lb	2.0
Barite, lb	117.32
Calcium Carbonate A, lb	25
Calcium Carbonate B, lb	25
Properties	
Mud Weight, lb/gal	11.2
Oil / Water Ratio	75 / 25
Electrical Stability, volts	360
θ 600 / θ 300 @ 120°F	50/30
θ 200 / θ 100	23/15
θ 6 / θ 3	8/7
Plastic Viscosity, cP	20
Yield Point, lbs/100 sq ft	10
10-sec Gel, lbs/100 sq ft	8
10-min Gel, lbs/100 sq ft	10

Table 3

PSD match of Pore Target with Variance (Case 4)

D Value	90	75	50	25	10
Target Size	45.0	13.3	6.6	2.9	2.0
$CaCO_3$Blend	59.2	24.1	9.1	3.8	1.3
Variance	14	11	3	1	(1)

Table 4

Dynamic Filtration and Return Permeability (Case 4)

Core ~ k_i [mD]	Dynamic Filtration [gal/ft^2]	Return Permeabilit, % k_r
700–800	0.27	91
200–300	0.28	95
50–75	0.39	>100

5. CONCLUSIONS

1. When sufficient pore data are known, reservoir drill-in fluids formulations may be designed to develop less damaging filter cakes when all interparticle gaps are tightly filled.
2. When sufficient pore data are known, the Vickers Method of sizing particles to satisfy all 5 target parameters, will result in high return permeability values in the laboratory.
3. Pore throat distributions found in nature tend to be wide and cannot be described with one measurement.
4. A specific distribution of particle sizes is required to effectively bridge a pore throat. This distribution must include particles that are smaller and larger than a third of the pore throats diameter.
5. The concentration of bridging material required should be above 30 lb/bbl for WBM but maybe reduced in OBM.
6. The Vickers method works with OBM and WBM fluids.
7. When sufficient data are known, field muds may be designed to encourage maximum production by applying the Vickers Method.
8. When insufficient pore data are known, estimates of the Vickers pore size targets based on permeability estimates can be a useful tool to maximize production.
9. Fluid design based on the Vickers method for bridging particle selection surpasses the Abrams and IPT methodology.
10. It is essential to maintain low fluid loss in order minimize formation damage and maintain a retained high permeability. This is best achieved using the Vickers method.

NOMENCLATURE

bopd – barrels of oil per day
DIF – drill in fluid
HPHT – high-pressure high temperature
IPT – ideal packing theory
lb/bbl – pounds per barrel
mD – milliDarcy permeability
mbopd – thousand barrels of oil per day
OBM – oil based mud
PSD – particle size distribution
SB DIF – synthetic-base DIF
μm – microns
WB DIF – water- base DIF
WBM – water based mud

The authors would like to thank Baker Hughes Drilling Fluids and BP for permission to present this paper. Special thanks are also given to the Houston and Aberdeen laboratory personnel who generated the data that resulted in the Vickers Method described in this paper.

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