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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

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Abstract

All permeable formations have a degree of porosity which is created by fissures or pore openings that require a high sealing efficiency to facilitate the well's drilling and completion operations. When drilling these reservoirs, the bridging characteristics of a drill-in fluid (DIF) are vital to minimize formation damage. If excess fluid and drill solids are allowed to enter the formation without control, skin damage may prevent or reduce the flow of hydrocarbon recovery.

Natural reservoir formations tend to have a spread of pore diameters. When formulating a non damaging reservoir drill-in fluid, technicians typically consider either the mean reservoir pore diameter or a linear relationship of the largest pore diameters down to zero. Actual pore throat measurements indicate that this is a poor way to describe the size distribution of the pore openings found in natural reservoirs and hence an inefficient design criterion to select the bridging particles required to seal them quickly and effectively.

This paper presents a new method (model) for predicting the most efficient way to create a particle bridge on a formation face having a wide spread of pore throat sizes. Laboratory data, based on particle bridging distributions using this new model, are shown to be an improvement over two current industry methods. The improvement using this design has been effective in the field and has resulted high productivity.

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 percentage of regained permeability.

Other methods use static or dynamic filtration tests on a natural core face or ceramic discs to measure the spurt loss and total filtration rates. These tests provide data with regard to the effectiveness of the fluids' invasion control capabilities. Another important measurement is the "lift-off" pressure requirement of the filter cake. This value is important especially in low pressure reservoirs where the filter cake quality determines the reservoir's ability to remove internal and external cake deposition with minimal flow initiation pressures.

Based on the need to design fluids that control filtrate and solids invasion as well as low cake lift-off pressures, this paper focuses on the relationship between pore throat size and particle size distributions of bridging particles to achieve non damaging results in the field.

Formation impairment, or its prevention, as related to fluid invasion controlled by sized bridging particles, is co-related to several damaging mechanisms. For example, excessive filtrate invasion can directly promote relative permeability reductions by blocking and/or 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 pore diameters will minimize that damage.

Bridging Theory - Review

One of the early advances in reservoir bridging still used 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 reservoir. In these cases, fluid designs utilize a wide range of particles in an attempt to provide a wide range of bridging capabilities.[1]

An improvement to Abrams' guidelines is the practice maintaining a low concentration of drill solids.[6] Simple laboratory tests can easily demonstrate the negative effect of drill solids on a fluid's ability to control filtrate invasion under dynamic conditions - an indication of poor bridging efficiency. The dynamic filtration rates, Q_o, shown for three fluids (**Figure 1**) are plotted against time. All three fluids were tested on 5, 20, 35 and 60 µm ceramic discs.

The basic design for each fluid was identical, however, Fluid A contained 21 lb/bbl (2.4% v/v) Rev Dust and 25 lb/bbl graded calcium carbonate. Fluid B had only graded calcium carbonate. As can be easily seen, the filtration rates for fluid A on all the ceramic disc sizes were significantly higher than those for Fluid B which had low filtration rates. It is widely known that higher filtration rates will deposit more solids on a permeable medium, a condition leading to increase of wellbore damage. Similarly, less control of filtration also suggests an increase in solids invasion into the pore spaces.

Although drill-solids will always be present in drill-in fluids after drilling begins, 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 75-80% 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 diameters forms a straight line[8].

The IPT approach is based on an estimation of the median pore size estimated from permeability by taking the square root of the permeability (in mD)[7]. This would be accurate if the size distribution of pore throats in a reservoir were linear. In reality, this linear relationship does not exist and the most common pore throat diameter in a reservoir will not be the mean 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.

After numerous filtration and permeability studies based on pore throat size distributions of core samples, it was obvious that a new methodology would be required to increase the efficiency of fluid loss control 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 reservoir core permeability. By utilizing this data, a more efficient method of bridging control was devised, tested and verified in the field.

New Bridging Methodology

A large proportion of the production flow from a reservoir will come from the largest pore throats, thus these higher permeability/porosity zones 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, including most of the void spaces in the filter cake medium itself. In other words, close packing is a collective phenomenon requiring the utilization of a wide range of particles to initiate quick 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 inter-particle gaps. Without the gaps filled, filtrate, polymer and small particle invasion would result.

It is desirable to select a particle size distribution (PSD) that will efficiently and quickly bridge the largest, medium and smaller pore size fractions. These optimum PSD's should be 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 pore throat 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, "The 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 of largest 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 when adequate pore size data are known. **Table 1** shows the efficiency of three methodologies. The fluids were also tested on a sandpack permeameter 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 resist internal cake deposition from deep invasion of smaller particles.

Bridging Efficiency and Sandpack Permeametry

Separate samples of a typical water based mud (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 µm, a D50 of 20 µm and a D10 of 5 µm. This pore throat distribution size is commonly 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. Both spurt loss (after 30 seconds) and total fluid loss were measured.

The results of these tests clearly demonstrate that spurt and total fluid loss values can be improved by fluids containing bridging solids calculated by the Vickers selection method. The results also clearly demonstrate the need for a bridging solid concentration greater than 30 lb/bbl as recommended by Dick[7]. In fact, laboratory evaluation and field experience has shown that a concentration of 50 lb/bbl is more efficient at controlling filtrate loss than using lower treatment levels. As pore sizes increase towards the D_{90} 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 **(Figure 3)**.

The initial permeability (Ki) 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 to flow through the disc. The final permeability (Kf) was conducted in the same manner as the Ki. A return permeability is calculated as Ki minus Kf. The pressure required to lift the filtercake and initiate flow is also measured.

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

Laboratory and Field Case 1

This study was based on data obtained from the Schiehallion Field in the North Atlantic, West of Shetlands, 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 reservoir were 20 and 35 µm rated discs. From these results (**Figures 4, 5 and 6**), it was obvious that one of the formulations was giving very good filtration control. This formulation was selected for a full return permeability testing 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 laboratories 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 (PPT) apparatus. This is a modified HPHT fluid loss cell. Instead of filter paper in the cell, an aloxite disc is used. 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 by attrition during the drilling operation. 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 water	0.259 bbls
NaCl brine	0.121 bbls
KCl	0.481 bbls
Polymer viscosifier	1 lb/bbl
Polymer filtrate controller	6 lb/bbl
Calcium Carbonate A	25 lb/bbl
Calcium Carbonate B	25 lb/bbl
Glycol	3%
Lubricant	3%
pH buffer	1 lb/bbl

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

Laboratory and Field Case 2

This study involved evaluation of a 10.3 lb/gal water-based calcium carbonate DIF for a North Sea open hole 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 5, 10, 20, 35 and 60 µm disc sizes 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 utilized. 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.

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

1. 48-hr dynamic mud placement on core
2. 48-hr static mud placement
3. 10-min dynamic mud placement
4. 10-min dynamic displacement to brine
5. 24-hr static brine soak (800 psi overbalance)
6. Gravel pack and screen placement
7. 7-day static soak with gravel 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.

Laboratory and Field Case #3

This study was for the Farragon project for BP in the North Sea that utilized oil based mud (OBM) to drill the reservoir section, which was then gravel packed using brine carrier and completion fluids. Because the payzone was to be drilled with an OBM and because pore 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 permeametry tests. Again the pore throat data was studied, the diameters and proportional distribution information was fed into an in-house software package that modeled 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 fluid design. The plot of the bridging size prediction using the Vickers Method can be seen in **Figure 11**. Further evaluation tests were done on Aloxite discs to check the bridging efficiency and then the DIF was used in the return permeameter using Berea sandstone. After both OBM and WB 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, which is in excess of expected rates - and the wells are still on reduced choke with potential to produce even further rate. The fluids programs for these wells have had a dramatic impact on incremental production for the field.

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 (**Table 2**). This fluid was reformulated from existing fluid stock for reservoir permeabilities ranging from ~700 mD down to sub 1 mD. The bridging blend included barite (required for density) and the optimum calcium carbonate blend to satisfy the 5 targets defined by the Vickers Method and shown in **Table 3**. To confirm the required PSD blend, three Berea core samples were selected, (a) 700-800 mD, (b) 200-300 mD and (c) 50-100 mD range.

At an independent laboratory selected by the Operator, the SB DIF filter cake was deposited dynamically for 4 hours on three Berea core samples followed by 16 hours of static placement and an additional 2 hours of dynamic placement. The SB DIF 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 sodium bromide (NaBr) completion brine displaced the soak fluid. Flow was then initiated in the production direction with LVT-200 mineral oil. The dynamic fluid loss and percent return permeability results are shown in **Table 4.**

Because the return permeability results 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.

The laboratory tests resulted in an optimized fluids program that was then utilized in the field. Results from this application are pending.

Conclusions

1. When sufficient pore data are known, reservoir drill-in fluid formulations may be designed to develop low damaging filter cakes when all inter-particle 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 (PSD) is required to effectively bridge a given pore throat distribution. This PSD 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 may be reduced in OBM.
6. The Vickers Method works with both OBM and WBM fluids.
7. When sufficient data are known, field muds can be designed to result in 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 improves upon the currently used 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.

Acknowledgments

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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

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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
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**

Table 1 – PPA Filtration and Return Permeability
* *IPT-1 contains 30 lb/bbl and IPT-2 contains 50 lb/bbl*

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 2 – SB DIF Formulation and Properties (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 3 – PSD match of Pore Target with Variance (Case 4)

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

Table 4 – Dynamic Filtration and Return Permeability (Case 4)

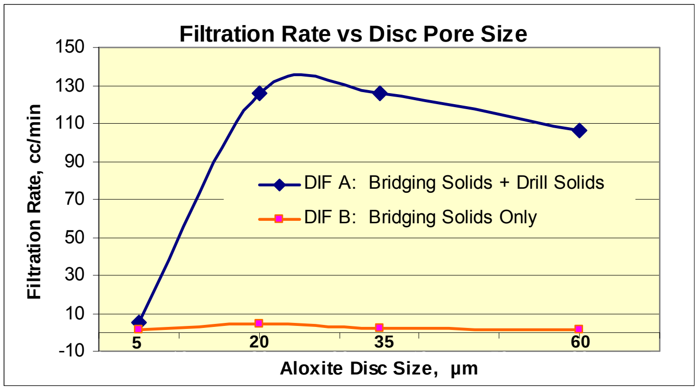

Figure 1 – Effect of drill solids/bridging solids relationship

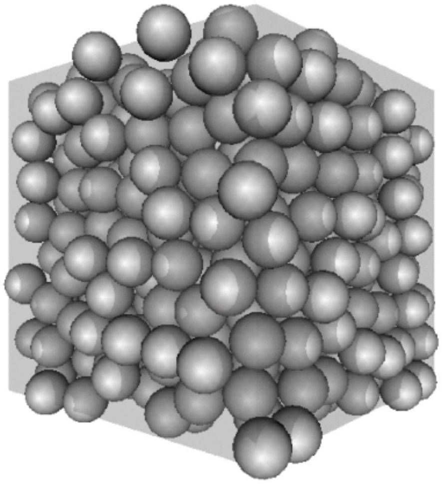

Figure 2 –Packing of Similar Spheres with Gaps

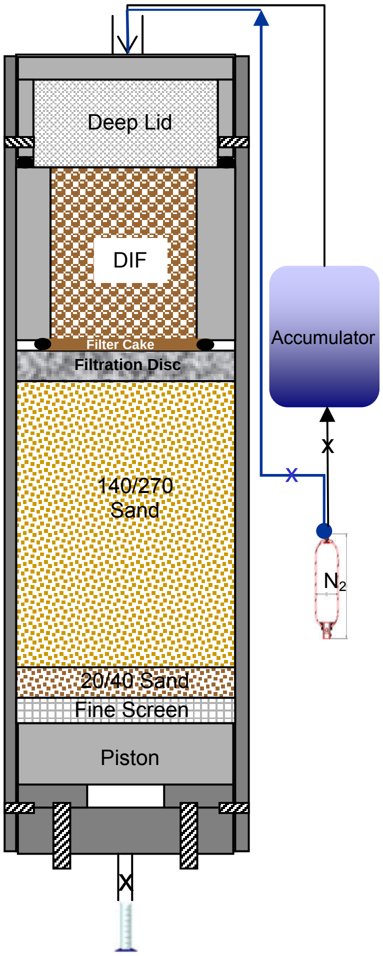

Figure 3 – Disc Sandpack Permeameter (Schematic)

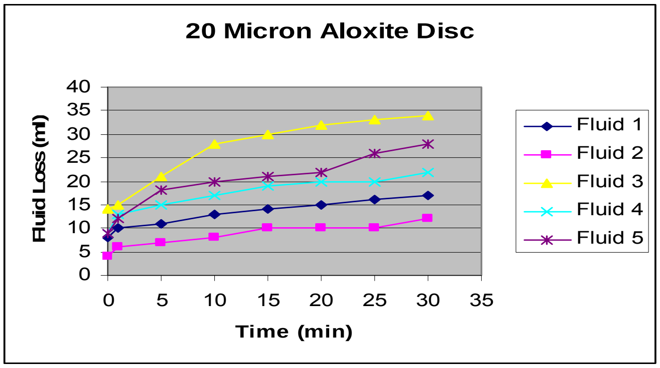

Figure 4 – Fluid loss on a 20 µm disc. Fluid 2 used the Vickers Bridging Method.

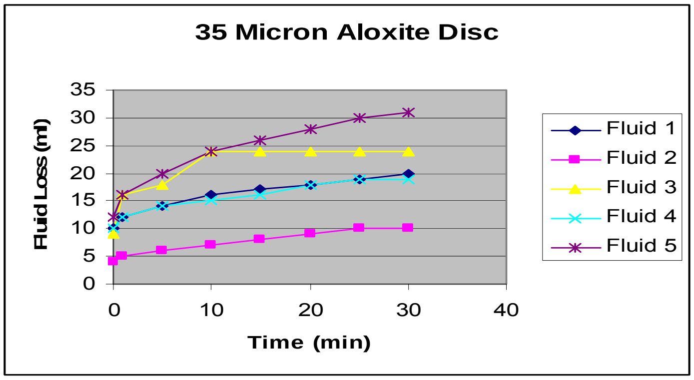

Figure 5 – Fluid loss on a 35 µm disc. Fluid 2 used the Vickers Bridging Method.

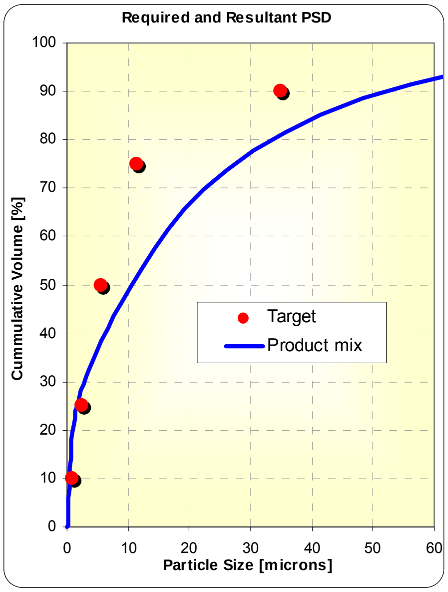

Figure 6 –Vickers Method PSD Fit (Case 1)

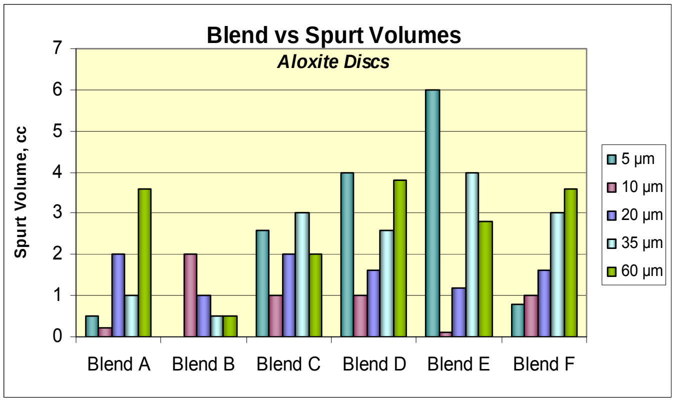

Figure 7 – Bridging Pre-design Study (1) Case 2

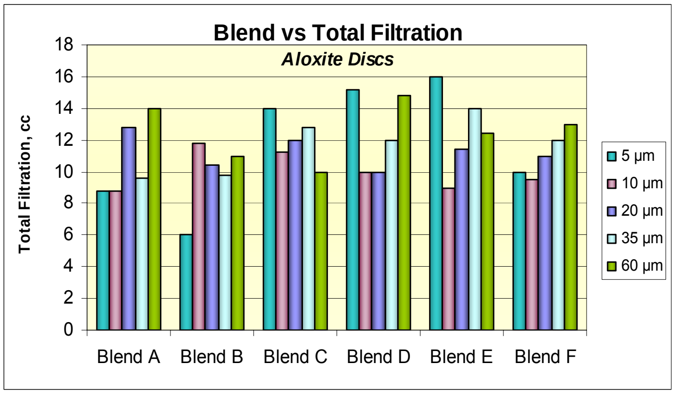

Figure 8 – Bridging Pre-design Study (2) Case 2

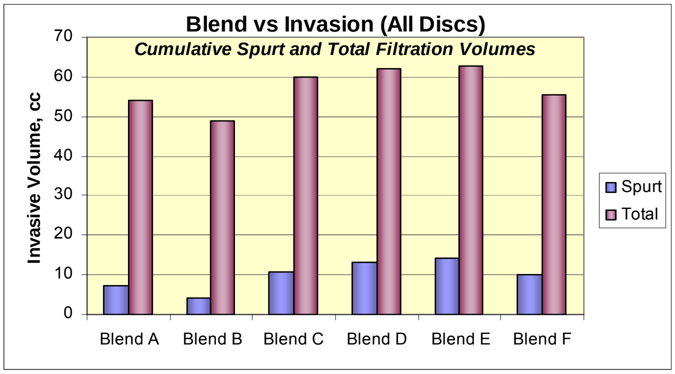

Figure 9 – Bridging Pre-design Study (3) Case 2

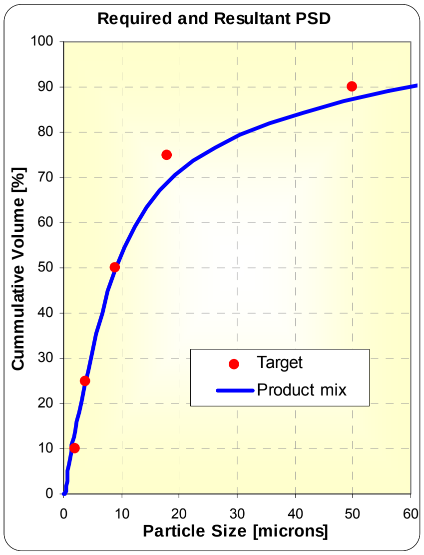

Figure 10 –Vickers Method PSD Fit (Case 2)

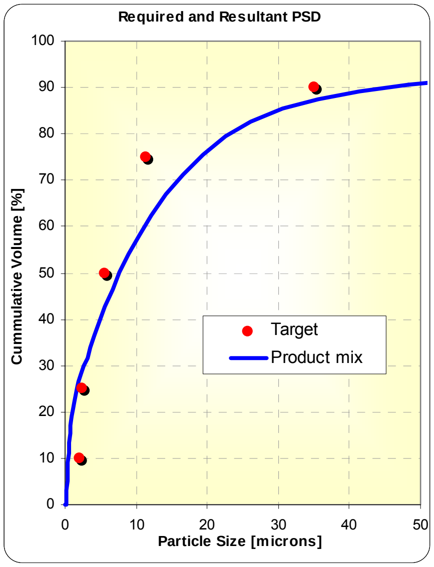

Figure 11 –Vickers Method PSD Fit (Case 3)