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Evaluation of Filter Cake Flowback in Sand Control Completions

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Abstract

Open hole gravel packing for sand control can offer productivity and cost reduction advantages over cased-hole completions, particularly in thick, high permeability sands. The filter cake formed by the reservoir drilling fluid can be trapped by the gravel, resulting in high drawdown requirements, non-uniform inflow profiles and/or low productivity. Effective clean-up and flow-back of this filter cake is necessary to fully realize productivity advantages of open-hole completions.

A comprehensive series of over 20 laboratory experiments were carried out to better understand filter cake flow-back in sand control completions. Variables investigated included mud weight and type, gravel size, additives like enzymes and acids, gravel size, and screen type. Results from 12 of these experiments are summarized in this paper.

Key findings include:

- Tested synthetic oil base muds resulted in filter cakes which were much easier to remove than those formed from tested water-based muds.
- 40/60 mesh gravel can severely inhibit filter cake removal compared to larger gravel sizes, which still maintain sand control.
- An expandable screen pressed into the filter cake does not inhibit filter cake flow-back as long as solids are sized correctly, i.e. the drill-in mud is properly conditioned at the rig site.

Experiments were conducted in a standard cell where filter cakes were dynamically deposited and allowed to flow back through gravel and/or screens at scaled flow rates – many with gas. Following each experiment, the entire cell was saturated with epoxy and thin sections were cut across the filter cake and gravel. These visual images dramatically complement return permeability and "lift-off" pressure measurements and help illustrate the mechanics affecting return permeability performance.

Introduction

Many new prolific reservoirs are being found and developed in high permeability sands. Completion of wells in these sands often requires some type of sand control to maintain sand-free, high-rate production. An increasing number of these wells requiring sand control are completed using open-hole techniques.

Completing the well as an open hole offers several advantages over other completion techniques including:

- Provide a simple lower cost and risk way of completing long intervals without complicated stacked multiple frac-packs and gravel packs;
- Provide an efficient completion in high mobility formations where the stimulation benefits of fracs are lost;
- Allow completion of long horizontal or high-angle wells.

Several studies have demonstrated the impact and dominance of perforation tunnels on the inflow performance of high rate wells.[1-4] Turbulence and limited in-flow area can hurt in-flow potential. Stimulation benefits of fracturing can be lost in high mobility (kh/viscosity) reservoirs as flow is choked by perforations. Area open to flow is significantly greater in an open hole relative to cased and perforated completions.

Until recently, many of these open-hole completions would have been accomplished with only screens in the open hole.[5,6] Several wells completed in this fashion have suffered premature failures due to screen plugging leading to productivity loss. In some cases this plugging led to such small inflow areas that screens were eroded and no longer able to hold back formation sand. Stand-alone screens are still a viable option for high permeability, well-sorted sands; but many heterogeneous formations require that the annulus between the screen and formation be stabilized by gravel or an expandable screen.

Although gravel solves many of the problems of screen-only completions by adding stability to the well-bore, backflow of the filter-cake can be inhibited by the gravel.[7-9] A filter cake trapped by the gravel can result in high drawdown requirements, non-uniform inflow profile and/or low productivity. To combat these problems, most mud and service companies market and use a variety of methods to aid with filter-cake cleanup for open-hole gravel packs. In addition to specially formulated mud systems, clean-up methods include use of enzymes, oxidizers, acid treatments and others. Chemicals to assist filter cake clean-up can be applied prior to gravel packing, during gravel packing with fluids added to the gravel pack fluid, after the gravel is in place, or combinations of all three.

Gravel packing is no longer the only option to obtain well-bore stability in an open-hole. Expandable sand screens have been successfully applied in various locations and would appear to offer many advantages. As brought to the market by Petroline (now Weatherford), an unexpanded screen is run in the open hole with a reduced diameter, then expanded out to the sand face later. The screen assembly consists of a slotted base pipe, and outer protective shroud and filtration media sandwiched between the base pipe and shroud. A cone is then run through the slotted base pipe to force the slots open and expand the diameter by up to about 50%. Holes in the outer protective shroud are also further opened during the expansion process. The filtration media, which has leaves of filter layer overlapped prior to expansion, slide over each other during expansion to maintain the original filtration integrity.[10]

The potential advantages of this completion system are many including: eliminating gravel pack operations, economic advantages by drilling a smaller borehole, large inner diameter for enhanced intervention capability, and a better chance at zonal isolation than gravel packs. One of the concerns with an expandable screen is the ability to flow back the filter cake after a screen has been expanded into the cake.

The purpose of this paper is solely to compare specific aspects of filter cake flow-back and clean up in the presence of sand control completion systems. It is not the purpose of this paper to compare or comment on various chemical clean-up methods, but to highlight the importance of mechanical lift-off mechanisms in the overall filter cake clean-up scenario. Specifically, we wanted to:

- Compare a synthetic oil based mud system to a water-based mud system. Both systems were "optimized" to maximize flow-back in the presence of gravel.
- Compare filter-cake flow-back with 40/60 gravel in place to flow-back with 20/40 gravel in place with comparable mud systems.
- Investigate filter cake flow-back in the presence of Weatherford's expanded sand screen.

Procedures

1.5-inch diameter core plug samples, approximately 3-inches in length, were drilled from outcrop Berea sandstone using 2% KCl as the coring fluid. The samples were each cut in half (1.5-inch long) to form companion sample sets. Sample brine permeabilities ranged from 300 to 500 mD.

A sample assembly (Figure 1) consisting of an upstream end-piece, an end-piece extensions, a 3/32-inch thick spacer ring (to allow for the circulation of mud across the face of the sample and the creation of a mud cake), the test sample, and a downstream end-piece all contained within a rubber sleeve was loaded into a hydrostatic coreholder, 1000 psi net confining pressure applied and a backpressure of 200 psi established. The test core was saturated with brine, temperature raised to reservoir conditions, and fluid flow was initiated in the production flow direction at the maximum flow rate. Fluid flow phase and maximum rate are listed in Table 1. The "base" permeability was thus established.

Next, the drilling mud was circulated across the injection face of the sample at an overbalance pressure of approximately 250 psi for a period of 16 hours. Fluid leak-off was measured but not discussed in this paper. The sample was cooled, the overburden pressure relieved, the upstream end-piece removed while not disturbing the mud cake and sample, the non-solid phase of the mud cake (fluff) removed using a syringe. If require, the appropriate gravel and treatment fluid were mixed to form a slurry. A bushing was inserted on top of the spacer ring replacing the end-piece extension, the bushing annulus filled with the gravel slurry, a coarse screen placed on top of the gravel pack, and the upstream end-piece re-inserted. The assembly was reloaded, the previous test conditions established, and the sample allowed to set of 16 hours.

Expandable screen assembly was used in place of the gravel for tests 9-12. In these tests, the screen assembly consisted of an expanded outer shroud (1/8-inch thick) and a filter media (150 micron). The shroud was placed within the 3/32-inch spacer ring (and pressed by hand into the filter cake). The screen assembly was then placed on top of the spader ring and held firmly in place for the duration of testing.

After reloading the cell and re-establishing test conditions, the same fluid used to establish the base case was then injected at a low rate and increased stepwise to estimate the filter-cake "lift-off" pressure. Maximum flow rate was determined by scaling expected reservoir rates and wellbore dimensions to the 1.5-inch diameter core-face. Humidified nitrogen was used for gas injection, 2% filtered KCl for water injection, and a refined 1 cP oil used for oil. Solids in the mud were determined by the mud companies with reservoir and test conditions in mind, using proprietary methods.

At the conclusion of testing, the sample was flushed with suitable solvents then the temperature of the system was increased to 220 F and dry nitrogen injected for 24 hours to dry the system. The sample was cooled, epoxy introduced into the sample from the injection end, and a longitudinal thin section cut across the gravel pack/mud sample interface. In some cases, a horizontal thin section was also cut across the mud cake.

Results

Test conditions and results are summarized in Tables 1 and 2 respectively. Tests contained in this paper are samples from distinct test series. Tests 1 and 2 were conducted to investigate differences between synthetic oil base muds and water based muds. Tests 3-5 were designed to look at filter cake clean-up with different gravel sizes for an oil reservoir. Tests 6-8 were looking at the same comparison of gravels for a gas reservoir. Tests 9-12 were part of a series of tests looking at filter cake clean up for an expandable screen candidate. These series of tests were designed to look at specific fields and conditions. Procedures and conditions were consistent within each series of tests, but tests from one series of tests should not be compared to another series. Furthermore, although care was taken to accurately represent down-hole conditions, caution is advised in scaling results to an actual well. These tests were designed to be used on a relative basis to compare specific variables.

A: Tests 1 and 2: Synthetic Oil Base Mud vs. Water Base Mud.

These tests were chosen to illustrate the dramatic and significant differences in the filter cake clean-up in the presence of artificial 20/40 proppant against the filter cake. Oil was used to flow back the oil-based mud, water for the water-based mud. Optimized treatments were applied to both: an oxidizing treatment for the water base[11] and a "Barascrub" treatment for the oil-based mud. As a result of these procedures, excellent return permeabilities were obtained in both cases: 54% for the water-based mud and 82% for the oil-based mud.

Thin section photographs of the filter cakes after flowing back however are remarkably different between these two tests. Run 1, using the water-based mud, is presented in Figure 2. Note that the filter cake is still essentially intact. "Lift-off" and return permeability are established by small "holes" or channels through the filter cake. It should be noted that similar observations were made for all water-based mud testing we conducted – including testing with acidizing and other treatment chemicals.

A thin section photo for Run 2, the synthetic oil-based mud case, shows a fundamentally different lift-off mechanism and result (Figure 3). In this case, virtually the entire filter cake has been removed from the core surface. What is left of the filter cake is either interspersed in the gravel pore space, or has been produced through the gravel. Again, this test and resulting thin sections are representative of all the oil-based testing we have conducted. Advantages in the synthetic oil based system, especially in the presence of gravel, are clearly evident by comparing the two thin section photographs in Figures 2 and 3.

B: Tests 3-5: 20/40 vs. 40/60 Gravels with Oil Flow.

As shown in Tables 1 and 2, Test 3 was conducted with no gravel, Test 4 with 40/60, and Test 5 with 20/40 gravel. All other test parameters were the same. Pressure vs. flow rate is presented in Figure 4. Note the dramatic increase in pressure needed to flow back the filter cake with the 40/60 gravel present. Similar results with return permeability are presented in Figure 5. In this case, permeability is plotted as a % of original permeability (as measured in the absence of a filter cake and described in the test procedures) as a function of cumulative fluid injected. Once again, it is apparent that the return permeability with 40/60 gravel is unacceptably low.

C: Tests 6-8: 20/40 vs. 40/60 Gravels with Gas Flow.

As in the three previous tests, all other test variables except the gravel were maintained constant. Also, as in Tests 3-5; plots of pressure drop and return permeability are presented in Figures 6 and 7. Once again, flow is severely inhibited by the 40/60 gravel.

It is clear from these two sets of results, that 40/60 gravel can severely restrict flow-back and clean-up of filter-cakes. Results help explain some of our field results where high skins and restricted inflow have been observed in open-hole gravel packs with 40/60 gravel. Another factor to consider in weighing the sand control advantages of 40/60 with the reduced inflow is the fact that uniform wellbore cleanup is also highly unlikely. Fluid is likely to be produced through only a small portion of the wellbore. Once fluid flow has initiated, insufficient energy will be available to clean-up the remainder of the filter cake.

D: Tests 9-12: Expandable Screen Testing.

Tests 9-12 were all conducted with 150 micron expandable screen and different mud systems as described in the Procedures. The purpose of this testing was to investigate the ability of filter cakes to lift off and flow back with the expandable screen in intimate contact with the filter cake. Contact between the screen and filter cake was comparable to the contact obtained between gravel and the filter cake in the gravel tests. A photograph of the loaded cell showing the imprint of the outer shroud in the filter cake is presented in Figure 8.

Because mud was changed between tests, each test was conducted with its own control test – that is, a comparable test was conducted without the screen present. That way, the effect of the screen could be ascertained by comparing return permeability and lift-off pressure data. This companion testing was conducted with the matching face of the cut Berea core to minimize influence of the permeable media used.

As can be seen from the tabular results in Table 2; the presence of the screen had negligible effect on the return permeability of the core – irregardless of mud system used. Test 9 was conducted with 12-pound water-based mud, Test 10 with 12-pound oil-based mud, Test 11 with 14.5 pound oil-based mud, and Test 12 with 11.8 pound oil based field mud. The 12-pound oil-based mud in Test 10 was weighted entirely with CaCO3, requiring 200 lbs/bbl of CaCO3 (compared to 35 lbs/bbl CaCO3) for Test 9. The purpose here was to investigate a worst-case solids scenario with acid soluble solids.

As can be seen in Table 2, lift-off pressure for Test 10 was exceedingly high, no doubt a result of the extraordinary amount of solids in the mud and filter cake. Despite the high lift-off pressure required, permeability return was excellent. Pressure and permeability results from this test are presented in Figures 8 and 9. Similar data for Run 12, which is typical of all the other testing, is presented in Figures 11 and 12.

It needs to be pointed out that procedures used in testing expandable screen filter cake removal are critical. Discussions with other investigators have revealed that some have obtained vastly different results. It is believed that these differences can be explained by differences in the force employed to hold the screen against the filter cake. If the screen is held against the filter cake and core face with the same overburden pressure used to contain the core, then filter cake removal is greatly inhibited. As mentioned earlier in our procedures, we firmly held the screen in a fixed place with respect to the core surface. We believe that this procedure more closely represents down-hole conditions.

Conclusions

- Flowback of synthetic oil based filter cakes appear fundamentally different than water-based filter cakes. In the presence of a confining gravel, oil-based filter cakes studied here completely lift-off and disperse in the gravel-pack, while the water-based filter cakes remain intact. This could have important consequences in the field where uniform lift-off and complete removal offers many advantages.

- Small gravel, like 40/60, can severely inhibit filter cake clean-up compared to larger 20/40 mesh gravel. Sand control advantages of 40/60 gravel need to be balanced with insuring good filtercake clean-up and flow capacity.

- There were no problems observed with flowing back filter cakes through an expandable sand screen; even with 14.5 lb/gal mud. Solids content of the mud does however need to be properly sized; 200 lbs/bbl solids did result in an unacceptably high liftoff pressure. Procedures employed in testing flow-back through expandable screens can have a significant effect on results.

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Tables

Table 1- Summary of Test Conditions

Test	Mud System					Treatment System	Sand Control System	Test System	
	Vendor	Name	Weight (ppg)	Other Solids	Base Fluid			Overbalance (psi)	Temperature (°F)
1	Tetra	Na/CaBr DIF	12.0	2.5% Rev Dust	Water	0.25 SR A.C.T.	20/40 Econoprop	200	220
2	Baroid	PETROFREE	12.0	3% Rev Dust	Oil	Barascrub	20/40 Carbolite	300	130
3	Baker	2% KCl PERFLOW	8.5	3% Rev Dust	Water	None	None	300	150
4	Baker	2% KCl PERFLOW	8.5	3% Rev Dust	Water	None	40/60 Sand	300	150
5	Baker	2% KCl PERFLOW	8.5	3% Rev Dust	Water	None	20/40 Econoprop	300	150
6	Baroid	BARADRIL-N	9.5	1.5% Rev Dust + 1.5% Sieved Core	Water	5% Enzyme	None	250	170
7	Baroid	BARADRIL-N	9.5	1.5% Rev Dust + 1.5% Sieved Core	Water	5% Enzyme	40/60 Sand	250	170
8	Baroid	BARADRIL-N	9.5	1.5% Rev Dust + 1.5% Sieved Core	Water	5% Enzyme	20/40 Sand	250	170
9	MI	FLO-PRO	12.0	none	Water	None	150 Micron ESS	250	180
10	MI	NOVAPLUS	12 (200 lb/bbl CaCO3)	none	Oil	None	150 Micron ESS	250	180
11	MI	NOVAPRO	14.5	4% Rev Dust	Oil	None	150 Micron ESS	250	180
12	Baker	OMNIFLOW	11.8	Field Solids	Oil	None	150 Micron ESS	250	180

Table 2 – Test Results

Test	Mud System	Base Fluid	Sand Control System	Flowing Phase	Maximum Flow Rate, cc/min	Return Permeability (%)	Lift-off Pressure (psi)
1	Na/CaBr DIF	Water	20/40 Econoprop	Water	6.0	54.1	2.0
2	PETROFREE	Oil	20/40 Carbolite	Oil	6.0	82.3	2.8
3	2% KCl PERFLOW	Water	None	Oil	5.0	64.2	1.0
4	2% KCl PERFLOW	Water	40/60 Sand	Oil	5.0	3.9	20.0
5	2% KCl PERFLOW	Water	20/40 Econoprop	Oil	5.0	25.1	4.0
6	BARADRIL-N	Water	None	Gas	60.0	51.1	1.0
7	BARADRIL-N	Water	40/60 Sand	Gas	60.0	4.1	20-40
8	BARADRIL-N	Water	20/40 Sand	Gas	60.0	29.7	2-4
9C	FLO-PRO	Water	none	Gas	60.0	42.5	3.0
9	FLO-PRO	Water	150 Micron ESS	Gas	60.0	37.3	3.5
10C	NOVAPLUS	Oil	none	Gas	60.0	36.5	4.0
10	NOVAPLUS	Oil	150 Micron ESS	Gas	60.0	31.5	40.0
11C	NOVAPRO	Oil	none	Gas	60.0	40.2	2.5
11	NOVAPRO	Oil	150 Micron ESS	Gas	60.0	30.6	2.5
12C	OMNIFLOW	Oil	none	Gas	60.0	40.4	1.5
12	OMNIFLOW	Oil	150 Micron ESS	Gas	60.0	36.3	3.0

Figures

Figure 1 – Schematic of Test Cell

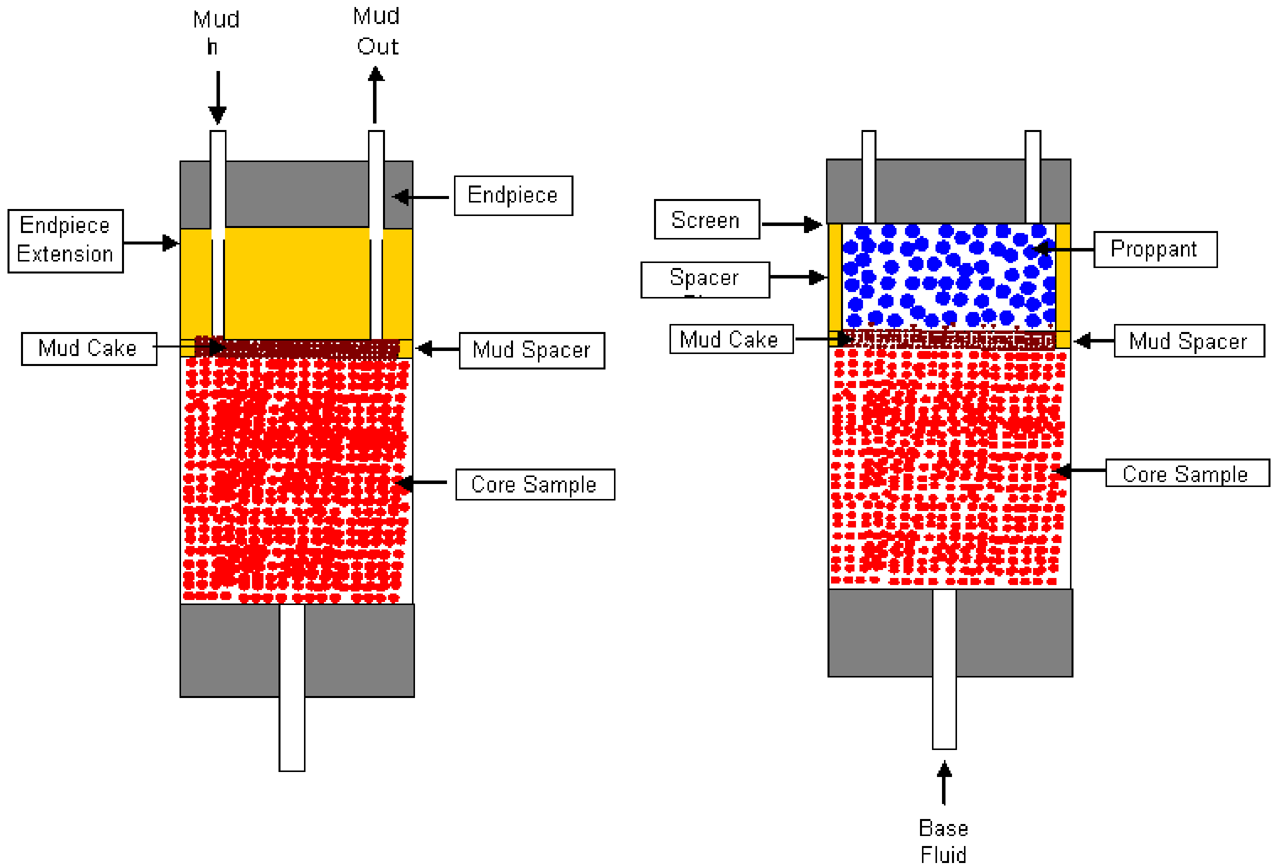

Figure 2 – Thin Section Photograph of Test 1 (Water-base mud) filter cake after flow-back.

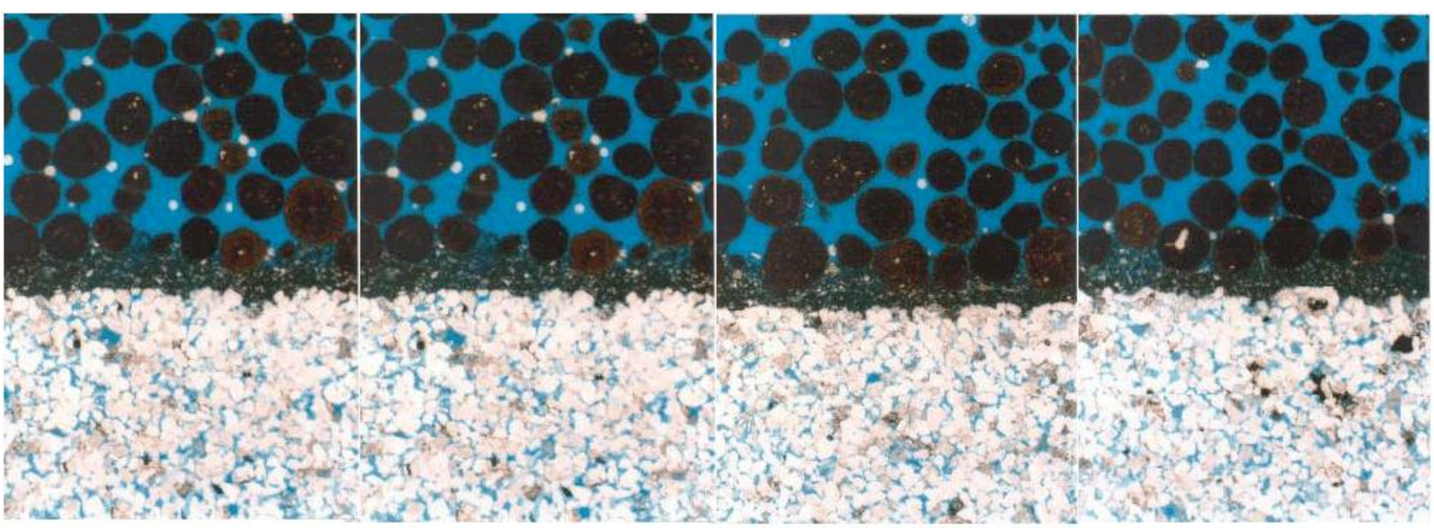

Figure 3 – Thin Section Photograph of Test 2 (Synthetic oil-base mud) filter cake after flow-back.

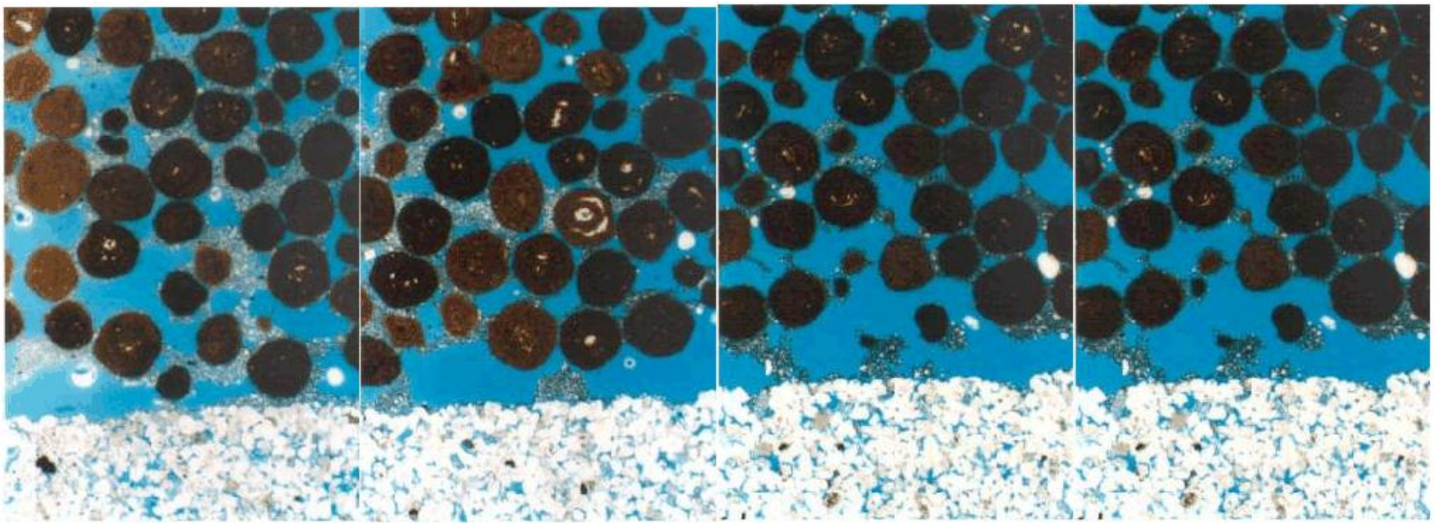

Figure 4 – Pressure drop across cell during filter cake flow-back for Tests 3-5

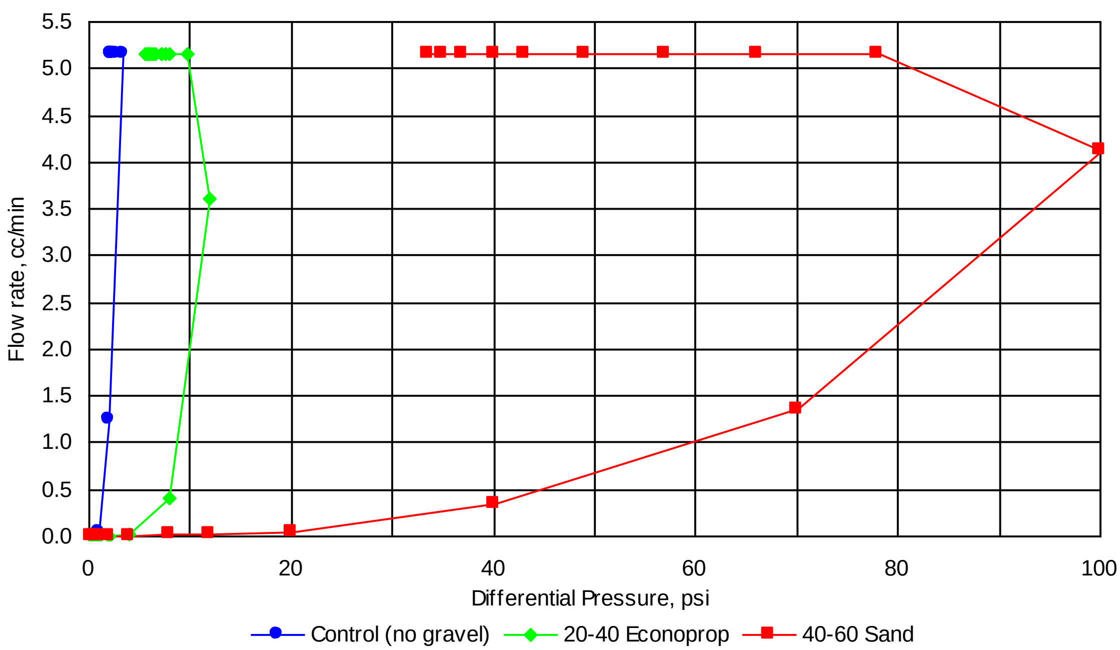

Figure 5 – Calculated return permeability results during filter cake flow-back for Tests 3-5

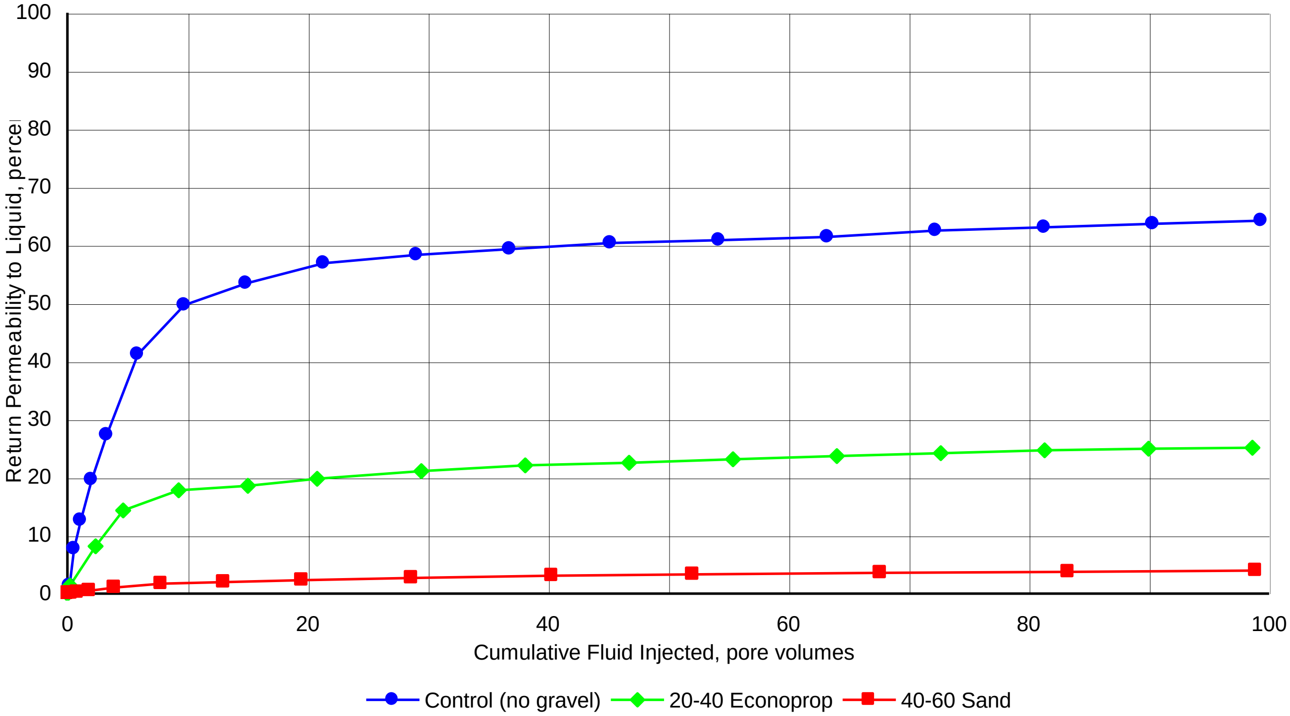

Figure 6 – Pressure drop across cell during filter cake flow-back for Tests 6-8

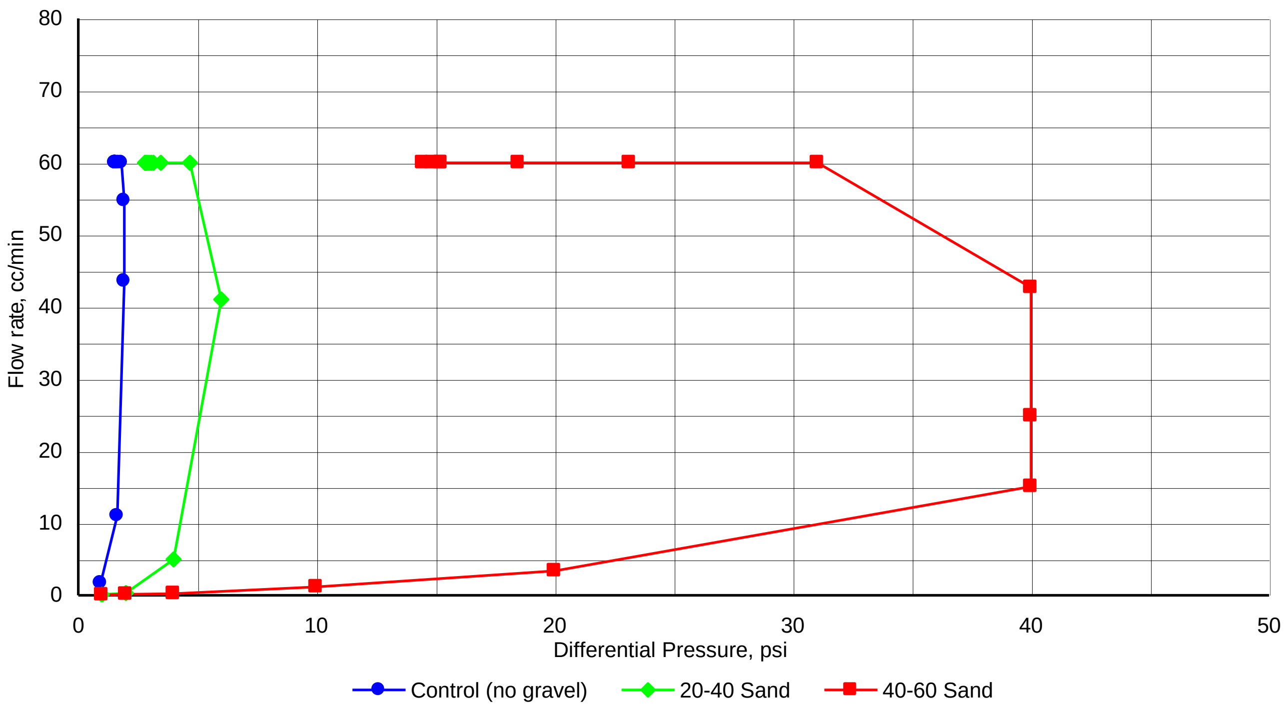

Figure 7 – Calculated return permeability results during filter cake flow-back for Tests 6-8

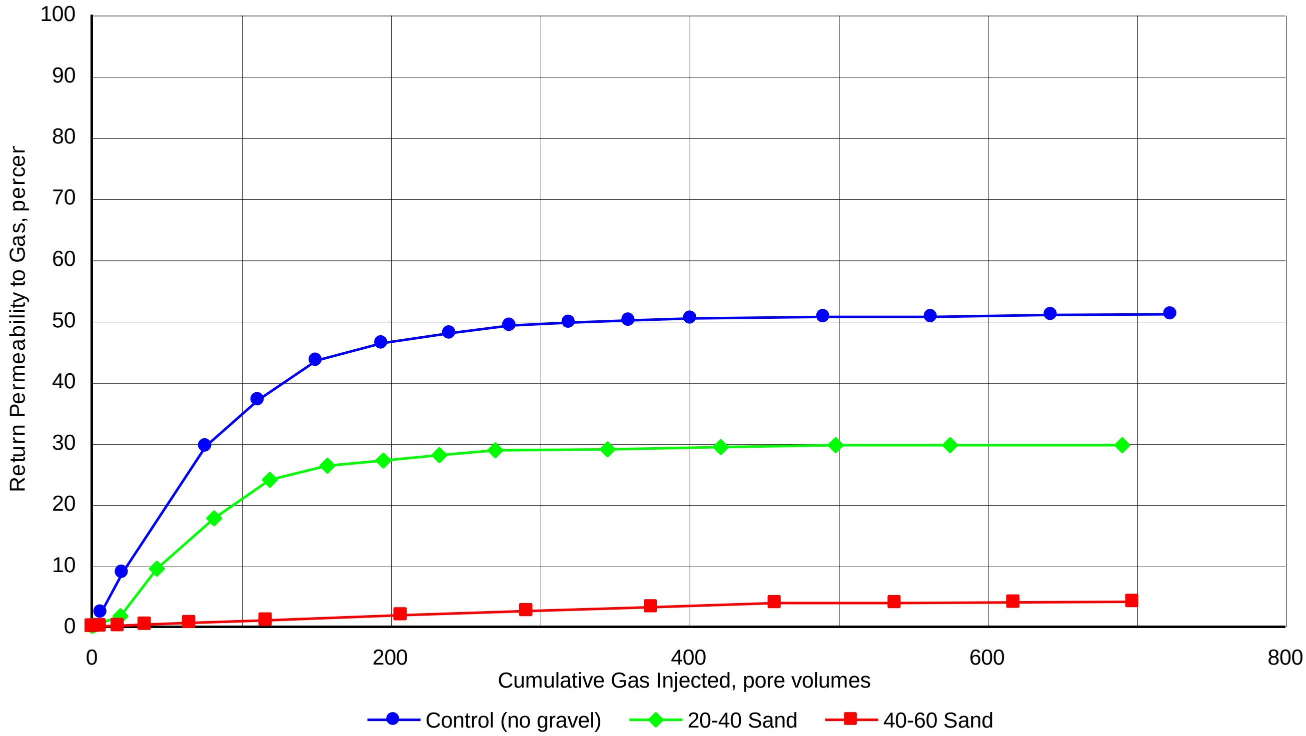

Figure 8 – Photograph of Filtercake showing imprint of outer expandable screen shroud pressed into filter cake prior to flow-back

Figure 9 – Pressure drop across cell during filter cake flow-back for Test 10 – Expandable Screen with high solids synthetic oil-based mud (and comparison to control test without screen)

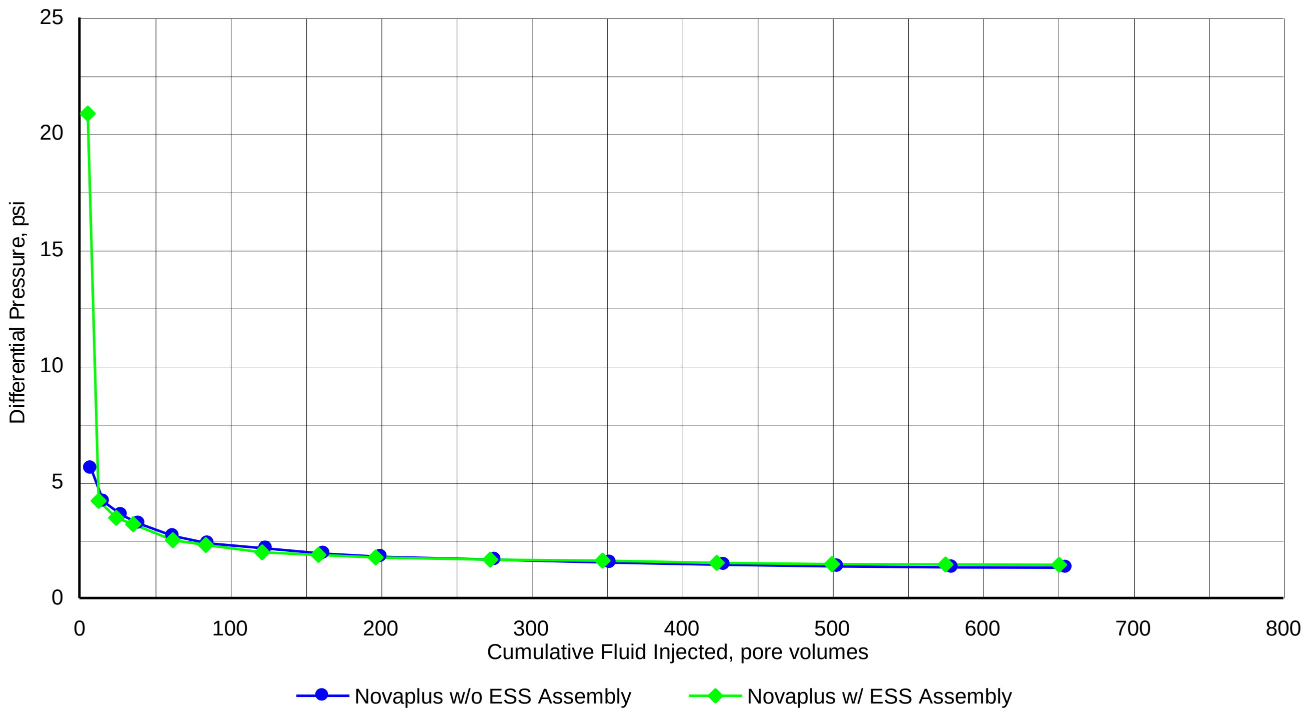

Figure 10 – Calculated return permeability results during filter cake flow-back for Test 10 – Expandable Screen with high solids synthetic oil-based mud (and comparison to control test without screen)

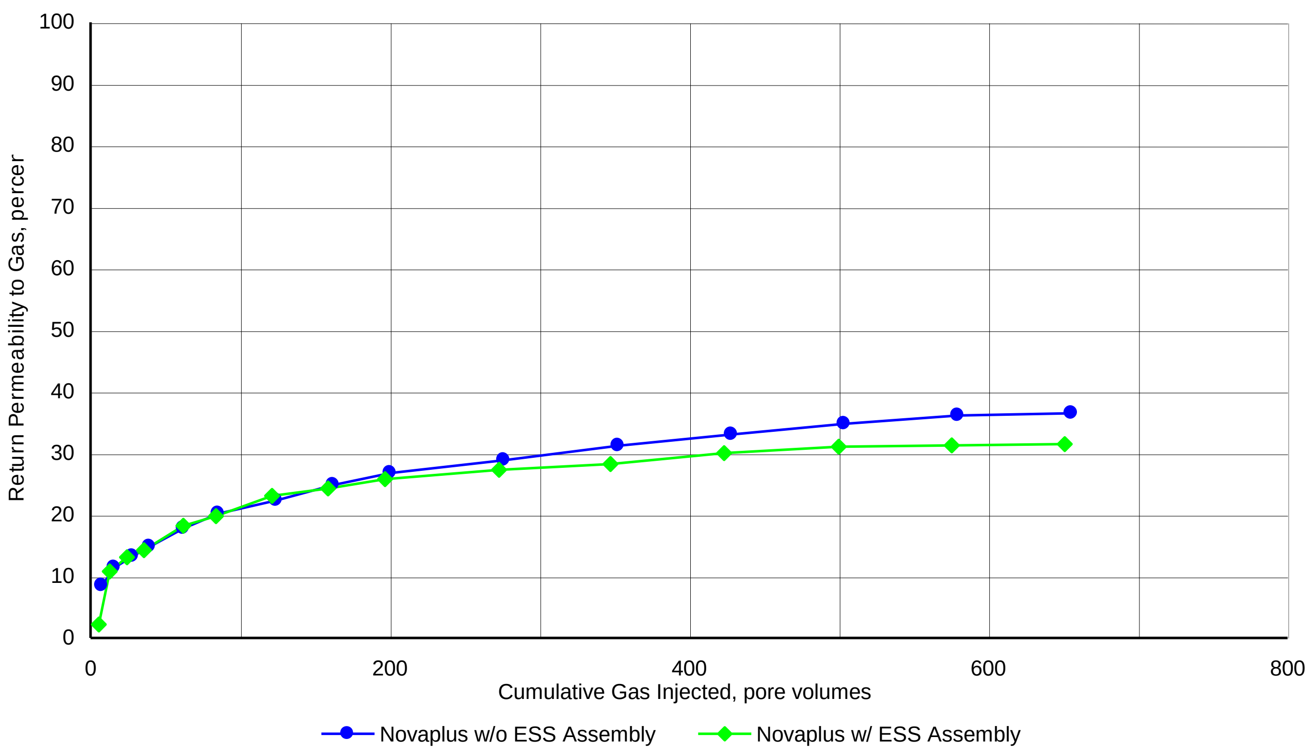

Figure 11 – Pressure drop across cell during filter cake flow-back for Test 12 – Expandable Screen with synthetic oil-based field mud (and comparison to control test without screen)

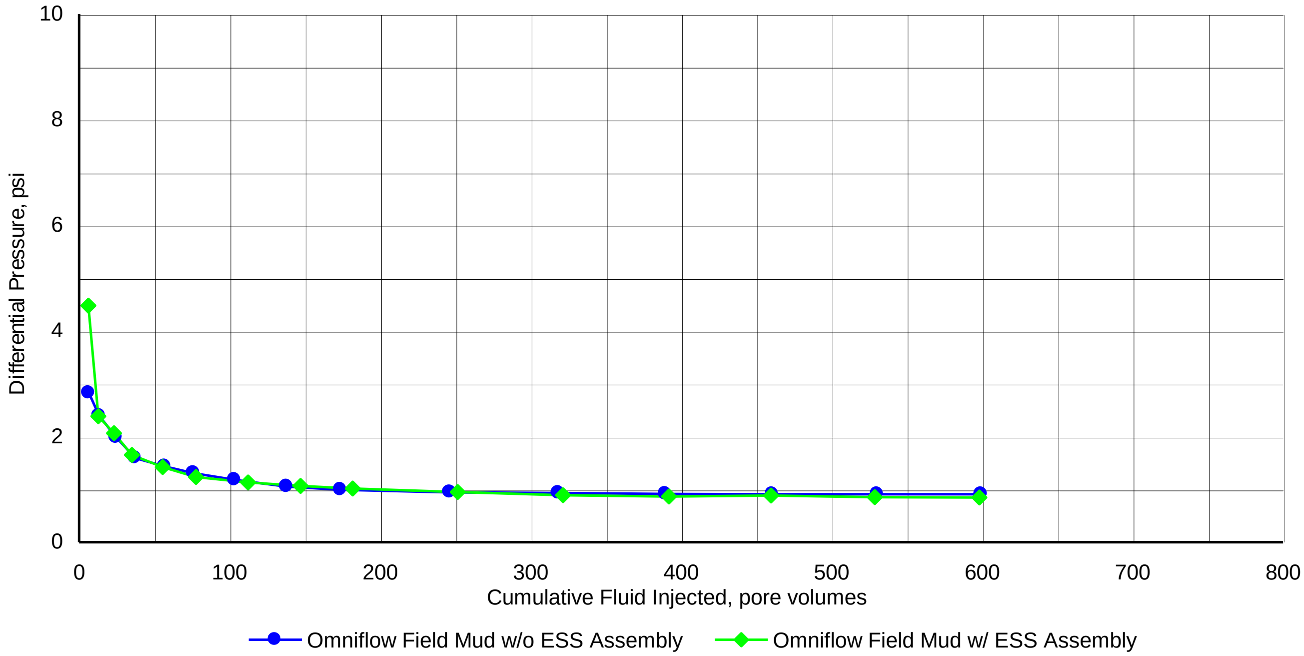

Figure 12 – Calculated return permeability results during filter cake flow-back for Test 12 – Expandable Screen with synthetic oil-based field mud (and comparison to control test without screen)