

Reversible Drilling-Fluid Emulsions for Improved Well Performance

Drilling difficult trajectories through reactive shales has forced drillers to make a choice: either use an oil-base mud to stabilize borehole shales and risk completion impairment, or drill with water-base mud that is easy to clean up and substantially increase drilling risk. Advances in drilling-mud chemistry now let drillers choose the best of both mud types.

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The use of oil-base fluid for drilling can bring with it an associated trade-off in formation damage. Laboratory tests demonstrate varying levels of formation damage and completion impairment associated with using oil-base fluids for reservoir drilling. These laboratory results are supported by field data. For a driller, oil-base muds control reactive shales, improve penetration rates and enhance overall drilling efficiency. For a completions engineer, the oil-wet state of the borehole, drilled solids and filtercake present well-completion challenges.

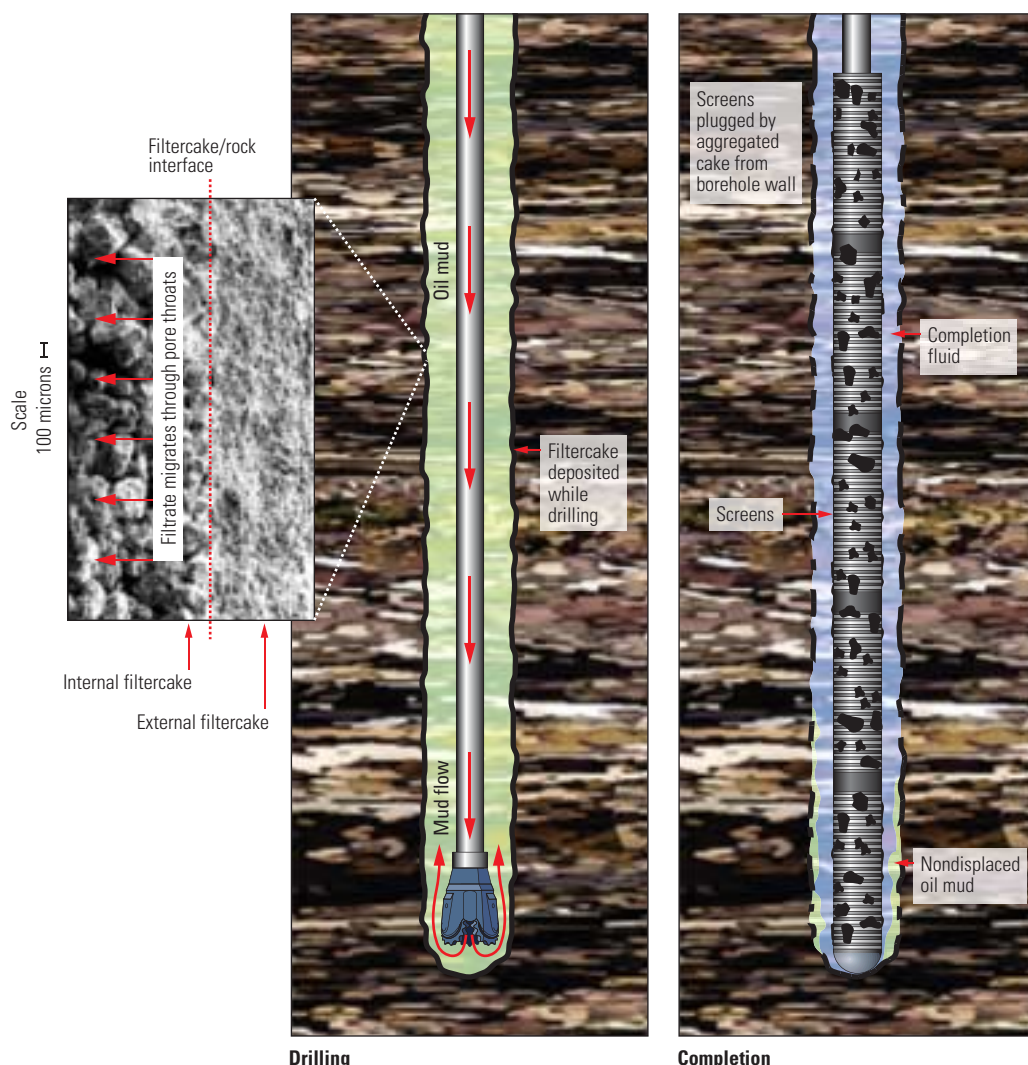
Ideally, a mud possessing both oil-external properties for drilling and water-external characteristics for completion processes would provide the ultimate solution for drilling efficiency and well performance. Advances in drilling-mud chemistry now let drillers choose the best of both: use an oil-base mud (OBM) while drilling to improve efficiency, reduce risk and stabilize the borehole, and then convert the OBM to a water-base mud (WBM) to improve cleanup and minimize completion impairment. In this article, we discuss the development of a dual-purpose, reversible-emulsion drilling fluid and show how one operator is applying this technology to improve well performance.

Impaired Well Performance

Well-productivity impairment resulting from using oil-base drilling fluid in a reservoir takes many forms. It may occur within the reservoir rock or at the borehole face, or it may relate to plugging of completion equipment and gravel packs by poorly displaced oil mud and oil-wet filtercake.

Large, solid particles in the mud form a filtercake on the reservoir rock face, as the drilling-mud filtrate invades the rock matrix. Smaller particles in the filtrate can aggregate and block pore throats, forming an internal filtercake ([next page](#)).¹ Oil-wet filtercakes, particularly cakes that develop inside the formation, are often resistant to chemical interaction and have small exposed surface areas, further limiting chemical mechanical removal.

The invading oil carries various oil-wetting surfactants into the formation. Although these are necessary to stabilize water-in-oil emulsions, surfactants passing through the reservoir pore throats may change the natural wetting state from water-wet to oil-wet, a process that impedes hydrocarbon flow through the rock matrix during production.² Tests have shown that an oil-wet state within a pore throat not only restricts hydrocarbon flow but also may increase the mobility of fine particulates, clays or other fine rock particles. Once mobile, these particles can plug pore throats, further reducing permeability.



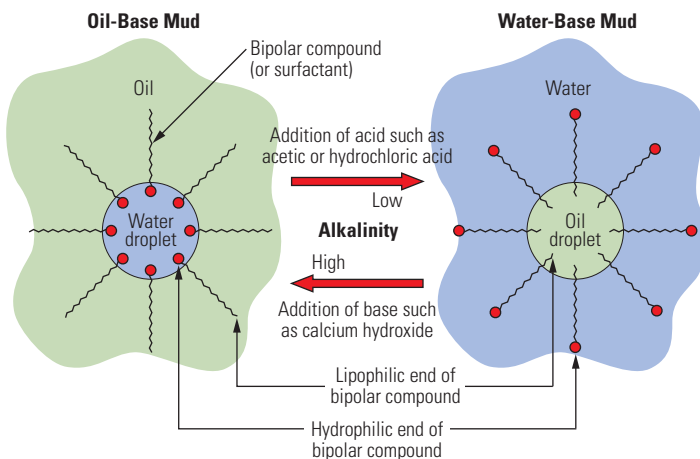
^ Reduced well performance with residual oil-mud filtercake. During drilling, filtrate is driven into permeable reservoir rock, leaving behind internal and external filtercake seen in the micrograph (*left*). Oil-wetting surfactants carried with the filtrate often alter the wetting state of productive pore throats and potentially mobilize fines, which have been made oil-wet. The deposition of low-quality filtercake, oil-wetting of surfaces and pore throats, and fines mobilization result in formation damage. Once the hole is displaced with completion fluid and production equipment is in place, residual nondisplaced oil-mud contaminated with displacement fluids, drilled solids and aggregated filtercake dislodged from the borehole may plug screens and gravel packs, reducing well performance (*right*).

After drilling and prior to running completion hardware, the fluid in the borehole is often displaced to a water-base completion fluid, usually a solution of various salts. During this displacement, chemical washes and viscous spacers are placed in the solution to make surfaces water-wet, while helping to remove oil mud and residual oil-wet material from the borehole. However, due to their oil-wet state, oil-mud filtercakes and other oil-wet materials deposited during the drilling process are not easily dispersed or removed by cleanup chemicals.³ Emulsions composed of nondisplaced oil mud and displacement

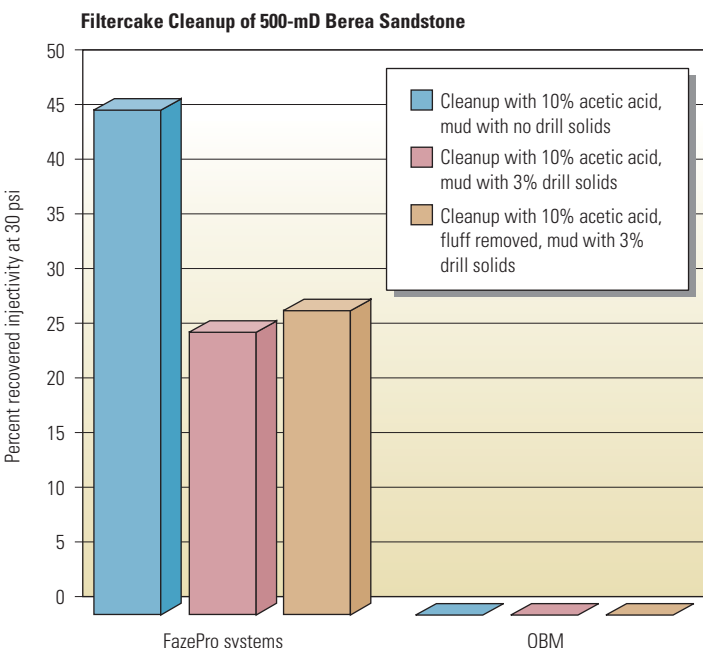
fluids often remain within the borehole. Once production begins, flow from the reservoir can mobilize these oil-wet materials, plugging completion equipment and gravel packs.

Formation damage resulting from external or internal oil-wet filtercake deposition, surfactant effects, fines plugging or mobilization, and plugging of completion equipment and gravel packs may significantly impair well performance, regardless of whether a well is designed for production or injection. The most obvious solution for avoiding oil-mud-related productivity impairment would be to drill the reservoir

1. Bailey L, Boek ES, Jacques SDM, Boassen T, Selle OM, Argillier J-F and Longeron DG: "Particulate Invasion from Drilling Fluids," paper SPE 54762, presented at the SPE European Formation Damage Conference, The Hague, May 31–June 1, 1999.
2. Ballard TJ and Dawe RA: "Wettability Alteration Induced by Oil-Based Drilling Fluid," paper SPE 17160, presented at the SPE Formation Damage Control Symposium, Bakersfield, California, USA, February 8–9, 1988.
3. Ladva HKJ, Brady ME, Sehgal P, Kelkar S, Cerasi P, Daccord G, Foxenberg WE, Price-Smith C, Howard P and Parlar M: "Use of Oil-Based Reservoir Drilling Fluids in Open-Hole Horizontal Gravel-Packed Completions: Damage Mechanisms and How to Avoid Them," paper SPE 68959, presented at the SPE European Formation Damage Conference, The Hague, May 21–22, 2001.



^ Adjusting alkalinity to reverse emulsion. The addition of acid or base compounds to the drilling fluid has the effect of altering the ionic strength of the hydrophilic end of the surfactant compound. In doing so, direct (oil in water) (*left*) or indirect (water in oil) (*right*) emulsions are created. This allows an oil-external fluid to be converted to a water-external fluid by adding a trigger compound such as hydrochloric acid and then changed back by adding a base such as calcium hydroxide.



^ Improved injectivity recovery. Tests were conducted on 500-mD Berea sandstone core to evaluate injectivity recovery. Laboratory-formulated FazePro systems were tested (*left*) and compared with similar formulations of conventional oil-base mud (OBM) (*right*). The first test (blue) contained no drill solids, while the second and third received 3% by volume simulated drill solids. In all tests, residual drilling mud and deposited filtercake were cleaned up with 10% acetic acid solution. In the second test (pink), excessive external cake, or fluff, was not removed prior to acidizing. In the third test (brown), the fluff was gently removed, without disturbing the firm filtercake deposited on the core face. Injectivity recovery for the FazePro system was between 25 and 45%, while all tests using conventional OBM indicated zero recovery.

with water-base mud. However, engineers often use oil-base drilling fluids to minimize risk and efficiently reach extended drilling targets.

Reversing Emulsions

In the mid-1990s, problems with oil-mud cleanup during completion operations prompted researchers and engineers at M-I SWACO to investigate the possibility of developing a reversible-emulsion oil mud.

An emulsion forms between two liquids when their interfacial tension is lowered, allowing a stable dispersion of fine droplets, the internal phase, to form in the continuous, or external, phase. Lowering the interfacial tension between dissimilar fluids often requires the presence of a bipolar material, that is, a molecule that has partial solubility in both phases.



^ Confirming emulsion reversal. When dropped in a beaker of water, droplets of this 9.4-lbm/gal [1.13-g/cm³] FazePro solids-free system remain intact, indicating an oil-wet state (*top*). After addition of 15% hydrochloric acid [HCl] to the FazePro system, the system disperses readily when dropped in the beaker, indicating that the system has reversed to a water-wet state (*bottom*).

In drilling applications, oil may be emulsified in the aqueous phase of WBM, forming what is called a direct emulsion. In OBM, the aqueous phase is emulsified in oil, commonly referred to as an invert emulsion.

To form an emulsion, bipolar molecules arrange themselves at the interface of the water and oil phases. The orientation of bipolar compounds at the water-in-oil (W/O) interface determines the type of emulsion. The chemistry and strength of the hydrophilic polar group compared with those of the lipophilic nonpolar group determine whether the emulsion forms as oil in water (O/W) or as W/O.⁴ With certain surfactants, varying the alkalinity of the fluid can modify the strength of the hydrophilic polar group, thus changing the nature of the emulsion (previous page, top left).

This understanding led researchers to develop the FazePro invert emulsion drilling fluid system. By adjusting the alkalinity of the

drilling fluid, engineers can reverse the emulsion from W/O to O/W, and back to its original oil-wetting state (previous page, right). During drilling, the FazePro system is oil-wetting, but during completion, the addition of acid reverses the emulsion, converting residual mud and oil-wet filtercake to a water-wet state.

Reversing the emulsion alters the surface-wetting characteristics of the solids from oil-wet to water-wet. This is important because the reversal alters the solid particulates in the filtercake to water-wetting, allowing acid-soluble fluid-loss control additives, such as calcium carbonate, to be dissolved. The integrity of the filtercake is destroyed, facilitating rapid and thorough cleanup.

The FazePro drilling fluid system provides the drilling performance and formation control of an oil-base fluid with the filtercake removal efficiency and nondamaging characteristics of a water-base fluid. Using this system, engineers are able to optimize both drilling and completion operations.



Injection Wells in West Africa

In Cabinda, Angola, oil fields operated by ChevronTexaco represent some of the company's largest and most prolific holdings. More than 450,000 bbl [71,505 m³] of oil are produced from these maturing reservoirs daily. Like operators of many aging oil fields, ChevronTexaco engineers in Cabinda use modern waterflooding

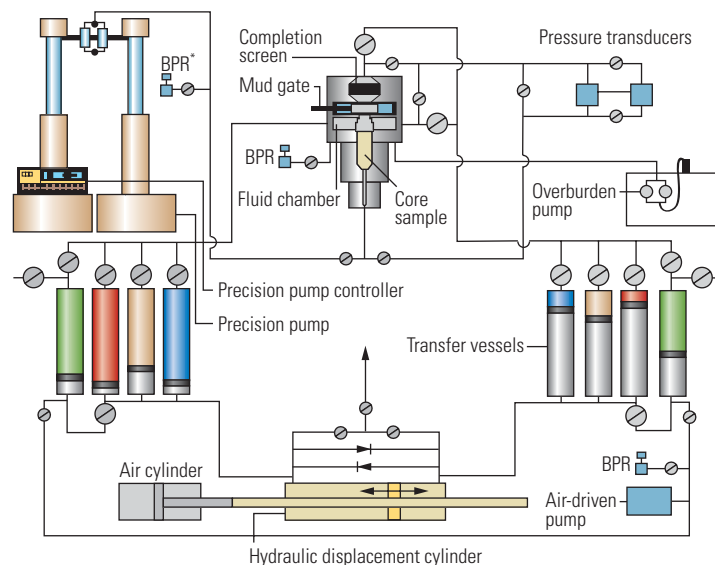
techniques to help boost recovery and maintain reservoir pressure.

This part of offshore West Africa presents many drilling challenges. Difficult well trajectories and drilling conditions are often addressed by using OBM to improve efficiency and reduce drilling risk. After drilling the reservoir sections with OBM, however, engineers found that injectivity was below expectation and difficult to remediate.

To deal with this injectivity problem, researchers at the ChevronTexaco engineering support center in Houston began a series of experiments and simulations aimed at improving injector-well performance in Cabinda. The first series of tests involved injectivity analysis on 500-mD Berea sandstone core material using conventional OBM representative of those used in Cabinda.⁵ For comparison, the FazePro system was evaluated under identical conditions.

An initial injection rate through the Berea core was established with filtered, synthetic seawater containing 3% potassium chloride (KCl) by weight. Prior to testing, the density of each drilling fluid was adjusted to 9.5 lbm/gal [1,138 kg/m³] using calcium carbonate. During a two-hour period, technicians used a modified high-temperature, high-pressure filtration test apparatus operating at 1,000-psi [6.9-MPa] differential pressure and 150°F [66°C] to deposit OBM and FazePro system filtercakes on 1-in. [25-mm] thick Berea sandstone disks. The muds were then displaced to base oil, followed by seawater and finally, by a solvent and organic-acid mixture. Each solution passed through the core for specific periods of time. A final injectivity was established using the same fluid and techniques as those used to determine initial injectivity.

These tests showed that injectivity loss caused by filtercakes deposited by the FazePro system can be at least partially reversed, while damage from OBM filtercake is persistent (previous page, bottom left). M-I SWACO researchers conducted further comparison tests to study the system. They used a laboratory completion simulator to deposit filtercake on a core (left). A treatment with cleanup chemicals was applied to disaggregate the filtercake. Fluid flow in the producing direction lifted the cake from the rock surface and transported it across a 40/60



* Backpressure regulator

■ Water ■ Stimulation fluid ■ Drilling fluid ■ Completion fluid

^ Screen-plugging test on the M-I SWACO laboratory simulator. This test apparatus (top) combines the features of a standard bidirectional permeameter with the ability to expose the mud filtercake to a stand-alone or prepacked screen without depressurizing the unit. This simulator allows dynamic filtercake deposition, displacement and flowback of up to four different fluids (bottom). The completion screen can be placed in the flow path while maintaining overbalance pressure and temperature.

4. Lipophilic pertains to an attraction for oil by a surface of a material or a molecule. This term is applied to the oil-wetting behavior of treatment chemicals for oil-base muds. In contrast, hydrophilic means having a strong affinity for water.

5. Berea sandstone is commonly used in the laboratory for injection and return permeability tests. Although natural, it displays heterogeneous pore structure and mineralogy with minimal anisotropy.

prepacked screen.⁶ Pressure-drop measurements across the screen indicated screen plugging with oil-base filtercake, but the filtercake deposited by the FazePro system disaggregated and flowed through the screen with only minimal loss of flow (right).

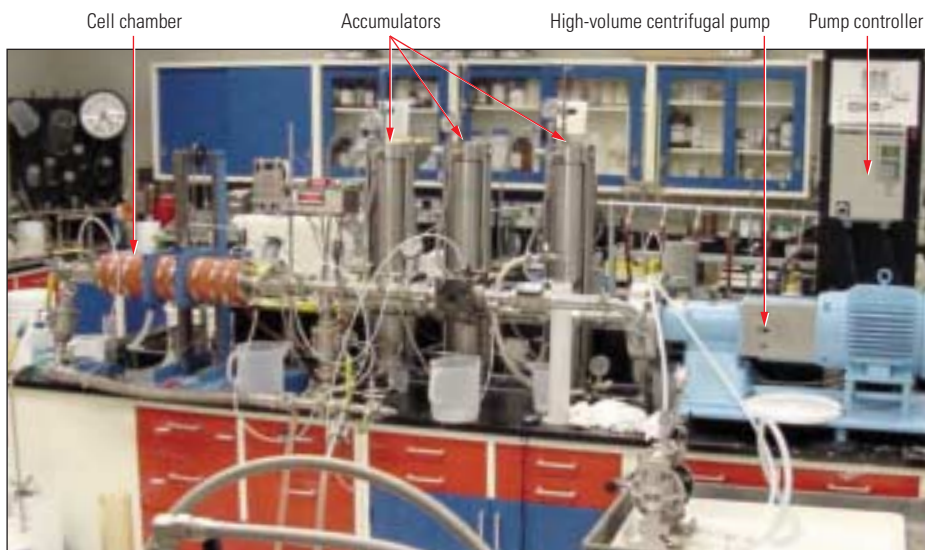
To validate these small-scale linear-flow tests, ChevronTexaco engineers used their radial-flow laboratory simulator to scale-up the volumes and to more accurately simulate mud placement, displacement and cleanup in a radial flow regime (below right). This equipment simulates flow rates expected in field conditions. In this series of tests, an OBM, weighted to 10.3 lbm/gal [1,234 kg/m³] with calcium carbonate, was compared with similarly weighted FazePro drilling fluid. Both mud systems contained 35-lbm/bbl [99.8-kg/m³] simulated drill solids. Initial injection flow was established with seawater. The mud was circulated at 150°F, under 500-psi [3.45-MPa] differential pressure through a 3-in. [76.2-mm] inside diameter by 4½-in. [111.13-mm] outside diameter by 6-in. [152.4-mm] long, 10-micron aloxite core.⁷ Following a sequence of circulation and shut-in times, technicians displaced the mud with base oil, followed by either a solvent and surfactant cleanup system for the OBM, or 10% acetic acid with 5% mutual solvent and corrosion inhibitor for the FazePro system. The cleanup package soaked for one hour before a final injection with seawater was established. After injectivity results were obtained, seawater was produced back through the core in the production direction. At the end of the test, a final injectivity profile was obtained.

Results from the radial-flow simulation show that the OBM filtercake was not completely removed from the core by either the initial displacement or by the subsequent flowback (next page). The injectivity profile for OBM showed zero injectivity after cleanup and 26% after flowback. The FazePro system filtercake was completely removed from the core after the acid soak. The injectivity profile showed a 49% injectivity after the acid soak and 52% after the flowback.

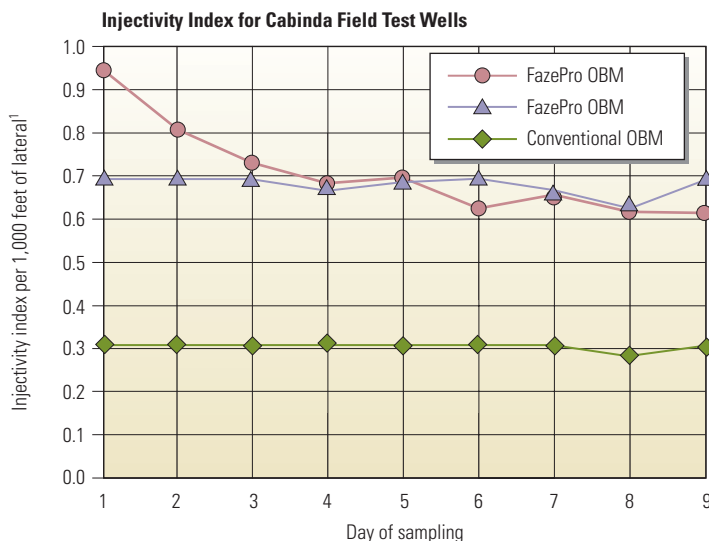
Supported by laboratory simulation data, engineers in Cabinda drilled the first of three multilateral injector wells using OBM. Four laterals were drilled and displaced with filtered seawater. Completion followed a treatment with a solvent spacer, several complete circulations with seawater, caustic pills, a CLEAN SWEEP solvent system for damage removal, spacer and 15% hydrochloric acid (HCl) solution that was in contact with the reservoir for 30 minutes.

Fluid Tested	Initial Pressure Drop across Screen	Final Pressure Drop across Screen
Conventional OBM	0.1 psi	300 psi
FazePro OBM	0.1 psi	0.3 psi

^ Minimal damage after flowback of the FazePro system. Screen-plugging effects of both conventional OBM and FazePro oil-base mud systems were evaluated using the completion simulator. When these fluids were flowed back across a standard 40/60 prepacked screen, a significant difference in pressure drop across the screen was seen. This indicated that the filtercake and other residuals from the conventional OBM had partially plugged the prepacked screen, while little flow impairment was seen with the FazePro OBM.

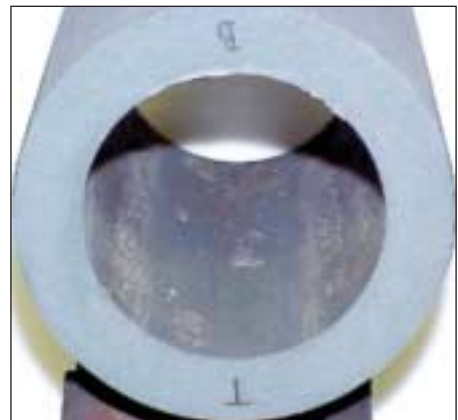
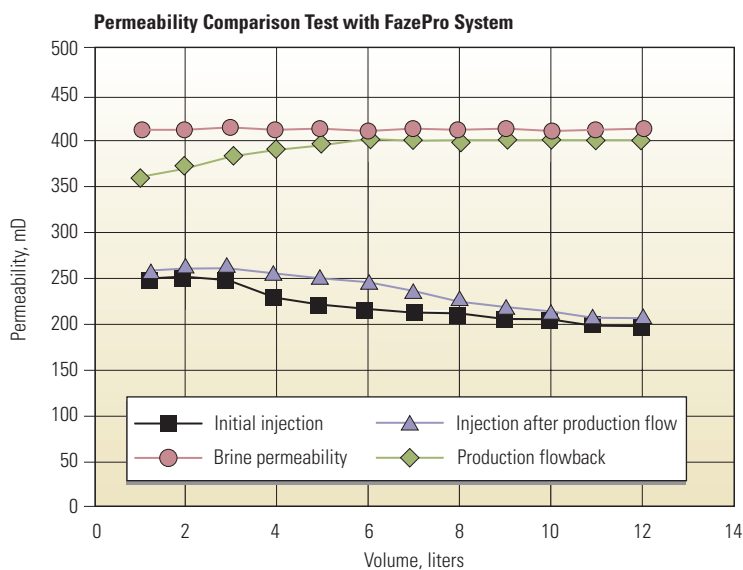
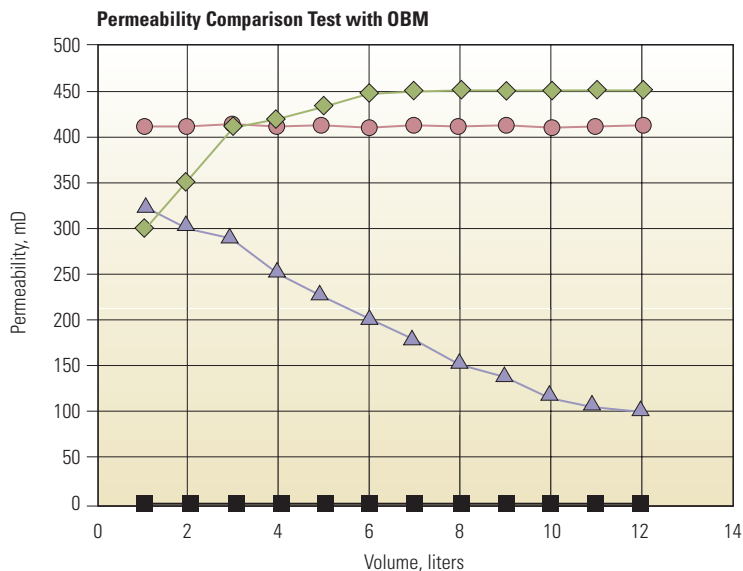


^ Evaluating FazePro systems in radial flow. The ChevronTexaco radial-flow laboratory simulator allows engineers to evaluate the effects of dynamic filtercake deposition under test conditions that are close to those in the reservoir. Tests can be conducted at temperatures up to 185°F [85°C], with 500-psi [3.45-MPa] working pressure, and fluid velocities of 350 ft/min [106 m/min]. The fluid to be tested is flowed radially through a rock core with an axial borehole—filtercake is deposited on the inside of the borehole, simulating actual downhole circulating profiles.



¹ Injectivity index = barrels injected/psi tubing head pressure

^ Improved injectivity index in field tests. Injectability was more than twice as high for the two Cabinda, Angola, wells drilled with FazePro systems (pink and purple) than for the one in the same field drilled with conventional oil-base mud (green).



^ Filtercake in core tests. Conventional oil-base mud and a FazePro system flowed radially through tube-shaped cores, leaving behind a mudcake on the inside face of the core (tan) (*top right*). After cleanup and flow in the reverse direction, considerable conventional oil-mud filtercake remains on the core, whereas only limited residue is seen on the FazePro system core face (*bottom right*). Data from the tests indicate a 50% drop in injection permeability (black) with the FazePro system (*bottom left*). The result from a similar test with conventional OBM (black) indicates poor cleanup and 100% loss in injectability (*top left*). Although injection permeability with conventional oil-base mud improved after flowing in the production direction (purple), injectability was not sustained.

The last two multilateral injection wells were then drilled with the FazePro system. The first well was completed with two laterals while the second was completed with four. In each case, the wells were filled with filtered seawater, jetted with 10% HCl, allowed to soak for five minutes, and then backflowed prior to injection.

Injectivity analysis on the three wells showed the injectivity index of both wells drilled with the FazePro system was twice as high as the well drilled with OBM, validating laboratory simulation data ([previous page, bottom](#)).

M-I SWACO and ChevronTexaco engineers continue to adapt the FazePro system to meet demanding drilling and completion requirements. Based primarily on data from Cabinda, drilling reservoir sections with the FazePro system routinely results in injectivity that is twice that expected from drilling with conventional OBMs.

Drilling for Production

Building on successful applications in injector wells, engineers in Cabinda now apply the

FazePro system to producing wells that require a more extensive cleanup treatment than simply producing fluids back. Since 2000, more than 35 hole sections in Cabinda have been drilled and

6. A 40/60 prepacked screen is composed of 40/60 US sieve size sand preinstalled in a screen assembly.

7. Aloxit disks are synthetic cores composed of aluminum oxide.

completed using the FazePro system; approximately 50% of the applications have been in production wells, with the other 50% in wells drilled for injection.

Longer multilateral wells have resulted in more difficult drilling conditions. In several cases, the use of OBM in areas where WBM was traditionally used to minimize completion problems has provided sufficient borehole stability to eliminate an intermediate casing string, saving both time and drilling costs.

Completions have also become more complex.⁸ Stand-alone screens, openhole gravel packs and expandable screens are becoming commonplace. To address these newer completion designs, procedures have been modified and new cleanup chemistries have been developed.

Hydrochloric acid or acetic acid, or combinations of the two, have traditionally been used to reverse FazePro systems and clean up the residual filtercake. Once a cleanup solution is pumped, disaggregation of the filtercake is immediate. With the borehole pressure in overbalance, removal of the cake on the borehole face often results in loss of completion fluid to the reservoir, reducing efficiency and increasing risk.

Recently, a FazePro system was used to drill the reservoir prior to an openhole gravel pack on the Kuito A-06 well, offshore Cabinda. Limitations in the tool configuration for this completion required a delay in emulsion reversal and cake removal, so that the completion-delivery tubulars could be pulled from the gravel-pack assembly without excessive or uncontrollable completion fluid loss.

To accomplish a delayed emulsion reversal, M-I engineers developed the FazeBreak chelant-base treatment that delays the disaggregation of a FazePro system filtercake. By incorporating the FazeBreak treatment in the beta phase of the gravel-packing operation, the chelant was placed in direct contact with the oil-wet filtercake, achieving a 4½-hour delay in emulsion reversal. This provided the driller with sufficient time to pull the workstring from the hole safely and efficiently. Similar to acid treatment, the FazeBreak additive dissolves the calcium carbonate fluid-loss and bridging material making up the filtercake, thus enhancing well performance by removing filtercake solids from the borehole and completion components.

Increasing Carbonate Reservoir Productivity

Drilling conditions in Mobile Bay, Gulf of Mexico, USA, are challenging. Bottomhole temperatures often exceed 300°F [149°C]. Significant structural dip commonly makes directional control difficult, particularly in horizontal wells.

To drill a 2,176-ft [663-m] borehole section in Mobile Bay Block 992, in 2003, ChevronTexaco, M-I SWACO and Schlumberger engineers developed an integrated reservoir-drilling and completion program. ChevronTexaco engineers chose a FazePro OBM system to help optimize drilling efficiency, minimize formation damage, reduce risk and provide the best possible conditions for directional control. The FazePro system had never been used at the high temperatures expected in this case—perhaps as high as 320°F [160°C]—but extensive predrilling testing at the M-I SWACO field support laboratory in Houston assured system stability and performance.

A horizontal reservoir section was drilled from 16,305 to 18,704 ft [4,970 to 5,700 m] measured depth and placed on target with no borehole- or mud-related problems. Lubricity imparted by the FazePro OBM system improved performance of downhole steering tools, allowing better directional control than had been experienced in previous wells drilled with WBM.

At total depth, the driller displaced the FazePro drilling fluid to a solids-free FazePro fluid. For improved compatibility with the completion fluid once the emulsion was reversed, the internal phase of the solids-free system was composed of a blend of sodium bromide and calcium bromide. The driller ran the completion assembly in the borehole and displaced the hole with sodium-bromide completion fluid.

Even though production tests exceeded expectations given the reservoir quality, engineers believed that acid stimulation would improve well performance. Although acid stimulation should be performed in a water-wetting environment, traces of drilling fluid and filtercake remain, regardless of displacement technique. This poses the risk of formation damage from emulsions as acid and oil-base fluids mix. On contact with acid, however, residual oil-wet FazePro materials become water-wet, thus minimizing any impact on acid performance.

Schlumberger engineers working from the DeepSTIM II offshore stimulation vessel pumped 60,000 gal [227 m³] of 15% hydrochloric acid (HCl) with 10% acetic acid in 10 stages, and 15% HCl VDA Viscoelastic Diverting Acid in nine stages at a rate of 30 bbl/min [4.8 m³/min]. In

this first use of VDA technology in the Gulf of Mexico, engineers successfully stretched the thermal and delivery-rate limits of the acid and delivery systems.

The acid treatment was delivered through a QUANTUM maX gravel-pack system for high-pressure, high-temperature conditions. On contact with the borehole, residual FazePro system filtercake became water-wet. Any remaining calcium carbonate bridging materials, now in a water-wet state, dissolved. The VDA system provided diversion, uniform treatment and maximum surface area contact by the acid.

Prior to acid treatment, the well was tested through 4-in. drillpipe at 5.6 MMcf/D [158,536 m³/d] with a flowing pressure of 1,200 psi [8.3 MPa]. After stimulation, the well flowed through 2½-in. and 3½-in. production strings at 15.88 MMcf/D [449,723 m³/d] with a flowing tubing pressure of 3,039 psi [21 MPa].

In this case, the engineering team chose an oil-wetting FazePro reservoir drilling fluid for thermal stability and drilling and completion efficiency. Internal and external filtercakes deposited in the drilling process were converted to water-wet, making them susceptible to removal by acid used to stimulate the carbonate reservoir. The integration of reservoir drilling-fluid technology, reversible-emulsion FazePro OBM, VDA technology and state-of-the-art delivery systems produced a threefold increase in production while minimizing cost and risk.

Building on Success

Operators and service companies develop and apply novel technologies to improve drilling efficiency and maximize hydrocarbon recovery. As drilling operations push the limits of depth, temperature, mechanical friction and completions technology, oil-base drilling fluids are evolving to meet the challenge. By integrating drilling, petrophysics and completion engineering, and approaching well construction holistically, today's oil and gas wells can be drilled and completed in a more efficient and cost-effective manner. Reserve recovery is optimized and individual well and overall field performance are improved.

With the development of drilling fluids such as the FazePro system, drillers no longer have to choose between improving drilling performance and decreasing the risk of completion impairment; they can have both. As operators and service companies work together, integrating drilling, completion and stimulation processes, the future promises even greater drilling efficiency and well productivity. —DW

8. For more on completion techniques: Acock A, ORourke T, Shirmboh D, Alexander J, Andersen G, Kaneko T, Venkitaraman A, López-de-Cárdenas J, Nishi M, Numasawa M, Yoshioka K, Roy A, Wilson A and Twynam A: "Practical Approaches to Sand Management," *Oilfield Review* 16, no. 1 (Spring 2004): 10–27.

9. Beta phase refers to the return gravel placement wave in a high-rate water pack.