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High-Temperature Reversible Invert Fluid Enhances Drilling and Completion Performance in Carbonate Reservoir

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Abstract

A recently completed horizontal gas-producer in a carbonate reservoir in the Gulf of Mexico presented numerous challenges for the drilling and completion phases. The primary objectives for this completion were to transect the target carbonate reservoir with a maximum horizontal wellpath and subsequently stimulate the entire lateral with an effective clean-up system while mitigating any formation damage.

The challenges included: bottomhole temperatures that exceeded 300°F, a relatively low-permeability reservoir that exhibited a wide range of isolated but relatively large pore openings, cleanup of a relatively long openhole lateral, "acid" gases that included H_2S and CO_2, and the optimization and design of the fluid and tool systems while mitigating costs.

This paper presents the planning and subsequent laboratory testing that was performed to optimize a reversible oil-based reservoir drill-in fluid (RDF) and a reversible solids-free system for the horizontal displacement. Of key concern were the prevention of any potential incompatibility, effective clean-up of the residual filter cake, and maintaining the inherent wettability. It was decided that the RDF must achieve at the very least the aforementioned primary concerns. In addition, the following issues were of equal concern: meet or exceed the local environmental objectives, minimize invasion and circumvent excessive fluid losses, inhibit any reactive shales, and maintain the integrity of the RDF system with respect to the relatively high-temperature environment. This paper includes the drilling, displacement and completion fluid systems. In addition, the authors present the initial flow test as well as the post-stimulation program, field results, and final well test.

Introduction

Traditionally, the petroleum industry defines high-temperature high-pressure (HTHP) as greater than 300°F and 10,000 psi respectively[1-2]. High static temperatures present challenges for maintaining mud properties and the longevity of the downhole LWD and MWD tools[3]. Oil-based drilling muds (OBM) are normally selected when drilling wells with bottom-hole temperatures in excess of 300°F[4]. This is due, in part, to their stability and predictable fluid properties that usually require minimum treatment and thus, low relative additive costs. OBM are normally re-usable, drill gauge hole, exhibit lower fluid loss resulting in a "thinner" filtercake, tolerate solids, saltwater, CO_2, and H_2S contamination, and provide lubricity. However, OBM present some potential problems. Among these are natural gas solution and the reduction in rate of penetration due to increased solids. The latter is generally the result of an OBM tolerance to higher concentrations of low-gravity solids[2]. The result is the OBM is stable; however, the rate of penetration decreases. Another potential problem is the presence of water in the filtrate, which, is usually the result of thermal degradation of the inherent emulsifier package. Left unchecked, this phenomenon can lead to wettability changes and full-scale breakdown of the OBM. Last, an OBM can be a cost disadvantage due to the potential for lost circulation.[5]

In contrast, traditionally water-based muds (WBM) are not the choice for high-temperature wells. This is due, in part, to common components that are thermally sensitive. As an example, WBM utilize organic polymers that if not treated for thermal degradation can lead to hydrolysis. In addition, high temperature gelation of WBM is due, in part, to low-gravity solids and can lead to an adverse increase in shear strength[6]. The free-water associated with WBM has a tendency to "cook" leading to unstability and ineffectiveness[2]. Rheological control is also a difficult challenge in a high-temperature environment[4]. Traditionally formates are the base brine of choice as a solution to the thermal integrity issues,[7] however the economic concerns may preempt this fluid as a choice. However, WBM exhibit some very attractive qualities, of which, cost-effectiveness and environmental friendliness may result in the definitive selection as an RDF.

In April of 2003 the authors initiated a comparative testing program that included confirming the integrity, clean-up, inhibition, and emulsion tendency of a reversible invert OBM, conventional OBM, and a WBM for drilling and completing a 2400-ft. lateral in the Mobile area of the Gulf of Mexico. A horizontal well had been selected to accelerate reserve recovery. The horizontal would be drilled laterally in an attempt to maximize the intersection of good quality reservoir rock. The rock properties appeared to vary on a foot by foot basis. A horizontal well was also expected to remain above any possible gas/water contacts. Of key concern was the ability of the selected cleanup system to effectively remove the subsequent residual filtercake and any potential near wellbore damage formed from any of the RDF systems. There was a concern that oil based mud emulsifiers may block the minimal porosity/permeability. In addition, there was a concern from a drilling perspective that WBM would not permit directional control required to drill the interval.

Project Location and General Geology

The proposed well was planned in the Mobile Field. This field is located off the coast of Alabama and Mississippi in the Gulf of Mexico, almost due south of Pascagoula, MS (Fig. 1). Several pipeline gathering systems currently exist in this area.

The proposed target was the Lower James Limestone. As the well was planned as a horizontal gas-producer, the well path would traverse the Middle James Limestone. It was desired to set the 7-in. casing across the partially depleted Middle James before drilling the horizontal. . The Lower James structural map is shown in Fig. 2. A cross-section map (Fig. 3) shows that the James Limestone is divided into three distinct pools: Upper, Middle, and Lower. The proposed well is plotted on this map. The James Limestone pools trend NW to SE and are the result of three transgressive-regressive (T-R) facies cycles of 7 million to 9 million years in duration that have been recognized in Lower Cretaceous strata in the Gulf of Mexico area. These are the LKEGR-TR 1 (Lower Cretaceous, Eastern Gulf, Transgressive-Regressive), the LKEGR-TR 2, and the LKEGR-TR 3, which include the Andrew Formation and Dantzler Formation (105 to 98 Ma) facies cycles. Two depositional cycles are recognized in the LKEGR-TR 1 facies cycle: the LKEGR-TR 1-1, which includes the Sligo Formation (121 to 118 Ma) and the LKEGR-TR 1-2, which includes the Pine Island Shale, "Donovan" sandstone and James Limestone (118 to 114 Ma) depositional cycles.[8] To date, oil and natural gas production in the northeastern Gulf of Mexico is chiefly from the fluvial-deltaic siliciclastic progradational lithofacies ("Donovan," Paluxy, and Dantzler sandstone reservoirs). However, significant hydrocarbon production also occurs from shoal and reef lithofacies such as the Sligo, James, and Mooringsport carbonate reservoirs.[8] To date, wells completed in Mobile blocks 991 and 992 have realized a total production of approximately 32.81 Bcf.

Completion Background

The horizontal was planned to intersect the top of the Upper James at a TVD of approximately 15,200 ft at 90° and set 7-in. casing. After cementing and drilling out, a 6-in., 2400-ft. lateral would be drilled to a total measured depth of approximately 18,700 to 18,800 ft (Fig. 4). For comparison, previous wells with TVD greater than 14,700 ft are also shown in Fig. 1.

Subsequently, the residual RDF would be displaced to a solids-free system and a ported-sub would be utilized to complete the lateral. The perforations in the ported-sub would be optimized by aligning with the most optimum reservoir rock. Next, a flow-test would be conducted without cleanup. Subsequently, the lateral would be acidized with a 15% HCl/10% acetic based-system. It was anticipated that the initial production rates would approach 8 MMCFG/D to 10 MMCFG/D and 150 BWP/D to 200 BWP/D.

The James Limestone carbonate has an estimated permeability that ranged up to a maximum of 20 mD. Based on a pore pressure of approximately 8.5 lb/gal and field experience, a 9.2-lb/gal RDF system was desired to drill this formation. It was also anticipated that trip and connection gases would contain CO_2 at about 5% and H_2S with estimated concentrations of just under 30 ppm.

Explanation of a Reversible OBM

A reversible invert emulsion drilling fluid is readily converted from a water-in-oil emulsion to an oil-in-water emulsion and potentially back to a water-in-oil emulsion using an acid-base chemical switch.[9-11] A novel surfactant package forms an invert emulsion in the presence of lime and a regular emulsion in the presence of acid. Protonation and deprotonation of the surfactant can be used to control the emulsion phase. However, the reversibility function at or greater than 300°F had not previously been tested in the field. The use of HCl/acetic acid readily and quickly changes the residual filter cake to a water-wet state and promotes disaggregation of the entrained solids. As the bridging solids entrained in the residual filter cake are calcium carbonate; once water-wet they are readily consumed by the acid. However, more detailed testing was required to fully test the functionality of the system for the anticipated reservoir conditions, primarily a bottomhole static temperature (BHST) of 295°F. However, the bottomhole circulating temperature (BHCT) was measured while drilling and ranged from approximately 260°F to 299°F. This suggested that the BHST was much higher. The benefits for utilizing a reversible RDF system with respect to this completion include; the ability to water-wet solids thereby mitigating plugging/sludging of the completion tools and the ability to utilize chemicals for a water-based cleanup.

Laboratory Testing

A laboratory testing program was undertaken to identify an optimum RDF. Three RDF systems were proposed: a reversible OBM-RDF, a conventional OBM-RDF, and a WBM-RDF. Of key concern was the ability to maintain rheological properties throughout the drilling of the lateral and subsequent completion. The laboratory data would be utilized to establish rheological and property targets and to develop a field maintenance schedule. In this manner, the RDF targets could be communicated to the field personnel for the purpose of establishing protocol and recommendations for common field problems that would not compromise the selected RDF systems integrity or potential to mitigate formation damage. It was also established that the laboratory data would be compared to the field data in order to document the differences to establish not only the validity of the selected RDF performance but the need for improving any properties that did not meet the proposed targets.

As such, the laboratory analyses would include petrophysical, compatibility, rheological, fluid loss, thermal integrity, and clean-up analyses.

Identified primary concerns for the RDF system included the following:

- Maintain the integrity of the RDF system
- Prevent potential emulsions
- Mitigate potential wettability changes
- Minimize invasion and circumvent excessive losses
- Effective clean up of the residual filter-cake
- Meet or exceed environmental objectives

Petrophysical Analyses

Several sidewall cores were available for analysis. Selected analyses included X-Ray Diffraction (XRD), Thin Section, and Cation Exchange Capacity (CEC). Nine samples were utilized for analysis (Table 1). These samples were collected from the MO991 No. 1 well. However, sample quality and quantity varied; therefore, only four thin sections were prepared. These sections were prepared using blue epoxy for ease of pore identification. A total of eight samples were analyzed for CEC. Nine samples were analyzed with XRD and only the bulk fraction technique was utilized.

Rheology and Thermal Integrity

The first phase of testing involved formulating a reversible RDF system that demonstrated: rheological properties, reversibility, and thermal stability for the anticipated 300°F-plus environment. The elimination of water or phase separation from the filtrate was critical and an excellent indicator of thermal stability. In all, thirteen tests were performed to delineate a formulation that exhibited stable rheological properties, reversibility, electrical stability (ES), and water-free filtrate. All formulations were blended using standard API protocol. The rheological and physical properties and electrical stability were documented before and after aging at 300°F.

A relative reversibility test was performed using 15% HCl. This test determines the amount of acid required to convert the RDF fluid from an invert emulsion to a direct emulsion as illustrated by its ability to disperse in a water column (Fig. 5). A lower volume of acid required for reversal is an indication of a more efficient reversibility to a water-wet state.

Design of Bridging Solids and Fluid-Loss Control

A proprietary software program was utilized to determine the optimum bridging solids blend for use in the reversible RDF system. This program utilizes a D½ rule for developing an ideal packing model[12] to optimize a best fit. The software was utilized to optimize the bridging solids to encompass the fine pores as well as large pores, approximately 300 microns by 500 microns, as observed in the thin sections (Fig. 6).

The next phase involved blending of lab-barrel formulations of reversible RDF using the optimized carbonate blend. Two methods were utilized to measure fluid loss. A modified high-pressure high-temperature (HPHT) cell was used that incorporated an aloxite disk on the bottom of the cell. The second method utilized a Permeability Plugging Apparatus (PPA). Two advantages with this second method are: 1) higher pressures can be utilized (approximately 2800 psi maximum depending on temperature) and 2) the effect of gravity/solids is mitigated. For the purposes of this testing, three different aloxite disks were utilized. This was performed to better simulate the wide variance of pore diameters that were anticipated in the drilling of the Lower James formation. After each fluid-loss test, the filtrate was examined for phase separation and/or the presence of water.

Compatibility Testing

This phase of the testing involved commingling of whole muds and their filtrate with completion brine (9.0-lb/gal NaBr) and acid (15% HCl). Three RDF systems (reversible-RDF, brine-based, and synthetic-based) were compared. The WBM-RDF utilized formate as a base and xanthan as a viscosifier. The SBM utilized IO16-18 as a base fluid. The reversible RDF utilized mineral oil then diesel as a base fluid. The comparative tests were performed using aliquots of the aforementioned systems at approximately 200°F.

The synthetic formation water was formulated utilizing a water analysis of a produced sample from the MO 991 No. 1 well. This synthetic formation water was commingled with the spent acid and completion brine to confirm the absence/presence of scale and/or precipitates.

Simulated Flowback and Clean-up Testing

This laboratory testing simulated the pressure required to lift-off a residual filter cake from an aloxite disk. This test was necessary as the well would be flowed before stimulation with acid. The anticipated initial production included water and gas, as such, synthetic formation water was utilized to initiate “lift-off”. Filter cakes were formed on aloxite disks, representative of the Lower James formation pores, using a modified HPHT cell. A digital gauge with 0.1-psi accuracy was used to determine lift-off pressure. The pressure was slowly increased using the synthetic formation water as a flowback fluid. The maximum pressure observed before the steady flow of formation water was recorded as lift-off. This procedure was utilized to compare the residual filter cakes formed from reversible RDF, SBM-RDF, and WBM-RDF systems.

In addition, a second test was performed to simulate the initial cleanup. Two systems were compared; a reversible RDF and a conventional OBM-RDF, both were diesel-based. As the completion called for the displacement of the lateral to a solids-free fluid, solids-free systems were formulated for both of the systems. The reversible RDF was optimized for minimal reversibility using the aforementioned method. The systems were commingled with acid at various ratios: 10/90, 25/75, 50/50, 75/25, 90/10 acid to aged reversible RDF SF, respectively. The commingled fluids were allowed to stand for 30 minutes at 200°F and observations were made and documented to determine the cleanest and sharpest break.

The next phase simulated the cleanup of the residual filter cake and solids-free fluids using the optimized reversible RDF and OBM systems. First, filter cakes were formed at 315°F for 24 hours using an aloxite disk and 500 psi differential pressure. After this period, the modified HPHT cells were opened and the residual mud decanted. A solids-free version of each system was poured into the HPHT cell and the cell was reassembled. Approximately 200-psi differential pressure was applied for 6 days at 315°F. This represented a worst-case scenario of the time period from when the lateral was displaced until the lateral was produced. After the 6-day period, the HPHT cell was carefully disassembled and the aloxite disk removed. The disks were then suspended in a beaker filled with 15% HCl, such that, one half of the aloxite disk was immersed. The acid was pre-heated to approximately 190°F in a hood to minimize exhaust of the fumes. The residual filter cake/disk was suspended for a total of 30 minutes. At the end of this period the disk and acid solution were photographed to document filter cake texture, formation of precipitates and/or phase separation. In addition, the reversibility and ES of the residual reversible RDF SF were determined.

To further confirm the integrity of the reversible RDF SF system, a Fann 70 was utilized. This test was performed for 16 hours at 300°F. The Fann 70 was programmed to perform a rheological "ramp" every two hours. The 600-rpm through 3-rpm readings and 10-sec and 10-min gels were recorded at the pre-assigned intervals.

Discussion and Results of Laboratory Testing

Petrophysics

Thin section and XRD data (Table 1 and Fig. 6) show the samples are limestone. Calcium carbonate is the dominant mineral phase, ranging from 16% to 100%. Other phases include dolomite (less than 1% to 80%) and anhydrite (less than 1% to 2%). Quartz was the only silicate phase detected and ranged from less than 1% to 3%. The only clay mineral detected was smectite; however, this phase was identified in only one sample that was recovered from the Upper James formation. Thin section micrographs of the samples from 15,067-ft MD, 15,069-ft MD, 15217-ft MD, and 15,277-ft MD show that these samples are micritic. Based on log and field data, only the sample recovered from 15,217-ft MD is from the Lower James formation. The samples from 15,067 ft and 15,069 ft are identified as Upper James formation. All samples exhibited pores that were isolated. Often, calcium carbonate had recrystallized to occlude pore space and calcite rhombs can be seen growing outwardly into pores. Fossil fragments were ubiquitous and dissolution of these fragments created isolated pores.

Rheology, Thermal Integrity and Bridging

Prior to testing it was known that the secondary wetting agent in the reversible RDF, which assists in HTHP filtration control, would have stability problems at 300°F. A series of tests were carried out to find supplemental HT fluid-loss-control agents. These included conventional emulsifiers and polymeric additives. It was also decided at this time to utilize diesel as a base fluid in the reversible RDF system for economic reasons. A final formulation (Table 2) utilizing No. 2 diesel provided good rheological properties and produced water-free filtrate and excellent reversibility. This formulation would then be optimized with respect to fluid loss using aloxite disks as the filtration media. The large pores observed in thin sections necessitated designing a carbonate blend that would encompass a wide range of pore openings. To confirm the integrity of the software-derived blend of calcium carbonate, it was decided to perform modified fluid-loss tests using three grades of aloxite disks. The disks have medium pore throat diameters of 13.5, 29.5, and 118.2 microns, respectively.

PPA fluid-loss using aloxite disks and the optimal calcium carbonate blend were measured at 295°F using 400-psi differential pressure. The subsequent fluid-loss values using the three aforementioned aloxite disks were extrapolated to 16-hr and ranged from 26 mL to 36 mL. The best fluid-loss control was exhibited on the 30-micron disk, approximately 26 mL for 16 hours.

Compatibility Testing

The first set of tests was performed to confirm the emulsion tendency of a reversible RDF, WBM-RDF, and SBM-RDF filtrates. In all cases an emulsion or interface was evident, most likely the result of the presence of emulsifiers in the filtrate. The addition of 0.5% v/v of a non-emulsifier exhibited a relatively clean break between the NaBr brine and filtrate under these test conditions. The presence of a phase separation by the WBM-RDF filtrate and emulsified pad by the SBM-RDF filtrate are also indicative of the necessity for a non-emulsifier. Further testing would be required to determine the optimum concentration for a non-emulsifier.

The next test was predicated upon the potential of the spent acid to emulsify the reversible RDF, WBM-RDF, or SBM-RDF filtrates. The additives and/or emulsifiers for the OBM systems accumulated as a pad between the two phases. This is most likely due to density and solubility differences. The WBM filtrate and spent acid exhibited an almost uniform phase with the exception of a pad that appears at the top. This pad is most likely the result of a difference in density between the two phases. In all three tests, no precipitates or sludge were apparent.

The next compatibility test utilized whole mud from reversible RDF, WBM-RDF, and SBM-RDF formulations. These were commingled with spent acid and then statically aged for 30 minutes. This test simulated the residual mud in the lateral section that could potentially contact the acid. The WBM-RDF exhibited a uniform phase with no separation; however the separation of additive(s) from the acid were evident at the top of the commingled solution. The SBM-RDF exhibited a phase separation and the water phase appeared turbid as the break was incomplete. The reversible RDF exhibited relatively good phase separation and the water phase appeared relatively clear (Fig. 7).

The final compatibility test utilized synthetic formation water that was formulated utilizing a provided water chemistry analysis. Aliquots of synthetic formation water were then commingled with 9.0-lb/gal NaBr, brine-based filtrate, and spent acid. No precipitates or scaling were observed. All fluids appeared homogeneous with the exception of the spent acid and simulated formation water as the acid additives migrated to the top of the resulting solution due to the density differences.

Simulated Flowback and Cleanup Testing

This phase detailed the integrity of the reversible RDF solids-free (SF) system and the potential for the acid to fully reverse this system to a water-wet state. To meet the density requirement of 9.3 lb/gal, this system would require a 13.3-lb/gal internal phase (60/40 OWR). In addition, if this system was reversed during the acid-stimulation phase of the completion, the preferred brine internal phase would be monovalent. Laboratory testing has shown that monovalent brines do not promote emulsions. Therefore, testing was undertaken to formulate an internal phase using NaBr. To meet the 13.3-lb/gal density requirement, solutions of 12.5-lb/gal NaBr and 14.2-lb/gal $CaBr_2$ were commingled. A two-salt blend was formulated using the maximum amount of NaBr (monovalent). However, $CaBr_2$ (divalent) was required to attain the desired density of 13.3 lb/gal. This formulation was then heated and cooled rapidly to confirm thermal integrity and stability. Fig. 8 shows the results. Note the clarity of this 2-salt mono- and di-valent brine. The measured clarity, using a turbidity meter, averaged 3 NTU for five readings. Based on the stability of this formulation after heating and the resulting clarity, it was decided to utilize this formulation as the internal phase.

The next test phases were undertaken to optimize the reversibility as well as the thermal stability of the reversible RDF SF. As the reversible RDF SF would remain in the lateral for up to 72 hours, it was critical that the system remain thermally stable and still reverse readily when contacted with the stimulation acid blend. The thermal integrity of the reversible RDF SF system was then tested using a Fann 70 apparatus. The test was designed to capture a rheological profile every two hours. This data is presented in Fig. 9 and shows that the plastic viscosity, yield point, and gels decrease for approximately 5 hours and then stabilize. The 16-hr rheological values exhibit relatively good stability. Consequently, this formulation was deemed “field applicable”.

The final phase compared the filtercake lift-off pressures of an SBM-RDF to reversible-RDF. This test utilized synthetic formation water and aloxite disks to simulate initial production. The lift-off pressure is reported as the pressure required to initiate “flow” through a residual filter cake above a hydrostatic pressure that is produced by synthetic formation water. Fig. 10 shows the residual reversible RDF and SBM-RDF filter cakes after “flowing” synthetic water. Note that the SBM-RDF filter cake appears as “broken” sheets, while the reversible RDF filter cake appears intact. The mechanism for “flow” is most likely pinholes allowing fluid to pass through the filter cake. The textural differences may, in part, be related to the formulation/additives that were utilized. The reversible RDF and SBM both exhibited relatively low lift-off, approximately 3.5 psi and 2.6 psi, respectively. This compares well with previous laboratory testing using a diesel-based system, which exhibited approximately 3 psi to 5 psi.

The final test for this phase compared residual filter cakes after contact with 15% HCl from a conventional OBM system to the reversible-RDF system. Filter cakes were formed on aloxite disks and allowed to age for 24 hr at 315°F. After this period, the residual mud was decanted and the solids-free systems of both fluids were poured into the modified HPHT cell and allowed to age for an additional six days at 315°F. Thereafter, the disks were carefully removed and transferred to beakers containing 15% HCl. The residual cakes were allowed to contact the acid for 45 minutes. The textural changes as well as any precipitates, emulsion, and/or scale were documented.

The residual OBM-RDF filter cake appeared as a relatively large mass that exhibits no chemical or physical decomposition. The residual reversible-RDF filter cake exhibited decomposition. A comparison of the beakers of residual acid shows a white "fluff" floating on top of the acid that was used as a breaker for the reversible-RDF filter cake. This material was tested for reversibility and yielded 5 mL.

Displacement Design

Field completion operations included two direct displacements: one entailed the reversible-RDF solids-laden in the lateral section to a reversible RDF SF system and the second entailed the reversible RDF solids-laden in the 7-in. casing to NaBr completion brine.

Both displacements were simulated using proprietary software. This program calculates required pump pressures and hydraulic horsepower as well as bottomhole, annulus, and tubing pressures. The user can estimate regime parameters for spacer trains as well as calculating velocities and Reynolds numbers. In addition, this program estimates Equivalent Circulating Density (ECD) at user-selected depths. For each displacement the following parameters were estimated and charted: estimated pump pressures and hydraulic horsepower, and ECD.

The first simulated displacement would be executed after drilling to TD. It would require displacing the lateral to approximately 400 feet above the 7-in. casing shoe. The total required reversible-RDF SF volume was estimated at approximately 125 bbl. This volume included a 10% safety factor for an out-of-gauge hole. In addition, this displacement included a 35-bbl slug that would be left in the drillpipe. The critical factors for a successful displacement were anticipated to be the ECD and minimization of pump pressure. The estimates for the ECD is reasonable and within accepted displacement practices.

The second displacement would be executed immediately after the first with the workstring/bit pulled to approximately 300 feet above the 7-in. casing shoe, allowing the displacement of the casing to the surface. This would entail displacing the casing from residual reversible-RDF to 9.2-lb/gal NaBr. Five spacers were formulated. The anticipated critical factors for this displacement were compatibility of the spacers, minimization of the ECD, and optimizing the pressure differential between the spacer train and the formation (>400 psi). The second spacer was critical for the success of this displacement as this spacer took advantage of the reversibility of the reversible-RDF system and included acetic acid to initiate this process. In addition, acetic acid was also incorporated into the third spacer to further ensure reversibility and water-wetting of the casing surface. The ability to maintain ±400 psi differential pressure during the displacement was established as a safety factor to ensure that the well would not flow. The spacer densities were adjusted to ensure this overbalance was maintained during displacement.

Based on the aforementioned results, it was decided that the reversible OBM could meet the drilling objectives; steering, lubricity, rheology, and hydraulics and provide a relatively easy clean-up while mitigating damage. The next phase would then involve the full-scale mix of the reversible OBM-RDF and the reversible OBM-RDF SF.

Plant Mixing

Preparations were made to transport the reversible RDF system and the reversible-RDF SF system on one boat. The displacement spacers were mixed at the same time, however, these were not sent to the rig until the lateral was complete. The initial mix called for 1500 bbl of 9.3 lb/gal with a 70/30 OWR. In addition, 125 bbl of the reversible SF were required. Reversibility testing with 15% HCl was used to QC all fluids mixed.

Three batches were mixed using the laboratory-tested formulation. Slight changes in clay and rheological modifier were required to attain the required specifications. Before transferring the three batches onto the boat, all tanks were inspected by a certified tankerman. The tanks were found sufficient and a total of 1495 bbl was transferred.

A 125-bbl batch of 9.3-lb/gal, 65/35 OWR reversible SF was also mixed. This system would be utilized for a balanced displacement after drilling the lateral as previously discussed. The ported-sub and packer would be run in this fluid. A 50-bbl portable blender was utilized for this mix. All three batches were transferred to a marine portable tank (MPT) and a final rheology check was performed on a composite sample.

Field Data

Drilling Results

In addition to standard drilling mud parameters that are generated and reported every 12 hours, selected key parameters were monitored. Contingencies were established in the form of a system maintenance schedule (prepared in advance) to address potential reversible-RDF incompatibilities, contamination from reservoir, drilling, or completion fluids, and thermal stability (Table 3). The primary objective was to maintain the reversibility of the reversible-RDF system at all times. A reversibility target of 20 mL was established and the contingencies included treating with primary emulsifier and reducing low-gravity solids (LGS).

Another key objective was to maintain the stability of the reversible-RDF system in lieu of the elevated BHT. Two key parameters, the excess lime and ES targets were established as greater than 1.5 lb/bbl and 300 volts, respectively.

Fig. 11 shows that the reversibility fluctuated between 15 mL and 65 mL. The elevated values are due, in part, to slugs and the reversible RDF system's exposure to the static conditions (*i.e.* BHST) during trips. Numerous trips were required for bit and bottomhole assembly (BHA) changes. This was largely related to the elevated bottomhole temperature. The highest values were recorded when a test was performed after a sample was caught from bottoms-up. The most stable values occurred while drilling the last 300 feet as no trips were performed.

Field PPA values are shown in Fig. 12. These tests were run on an aloxite disk using 1000-psi differential pressure at 300°F. The 30 minute totals, approximately 6 mL to 12 mL, agree well with laboratory PPA fluid loss simulating the same wellbore conditions.

Displacement Results

The first displacement utilized a reversible RDF SF system. Approximately 125 bbl of 9.3-lb/gal reversible RDF SF were utilized as this covered the lateral and approximately 300 feet of the 7-in. casing. The displacement began utilizing a 3-bbl/min rate. When the leading edge of the reversible RDF SF pill reached the toe of the lateral, the rate was decreased to 1 bbl/min. The displacement continued at this rate until the reversible RDF SF and a slug were theoretically spotted in place. No fluid losses were observed during this displacement. The second displacement utilized a five-spacer train. The calculated casing volume for this displacement was approximately 754 bbl. NTU's were monitored and after pumping approximately 0.94 hole volumes, the clarity dropped to 17 NTU's (Fig. 13).

Completion Assembly and Production Results

The cased interval was subsequently displaced to 9.5-lb/gal NaBr and dual ECP's were run to isolate bottom of hole at approximately 18409 – 18429 ft. Next, a 3½-in. ported-sub assembly was run that consisted of 10 separate subs. Finally, a packer was run and set at approximately 16,168 ft. The drillstring was displaced with nitrogen to 10,000 ft. and the well did not flow. The drillstring was then displaced to approximately 16,000 ft with nitrogen and tested for 14 hours. Initial test data showed a production rate of 2.8 MMCFD with 1626 psi FTP. The final rate exhibited approximately 5.5 MMCFD with 1151 psi FTP. The solids-free pill was subsequently produced-back and remained as an invert emulsion during the entire completion phase (Table 4 and Figure 14)

The lateral was subsequently stimulated with approximately 60,000 gallons of acid using nine diverter stages followed by completion brine. A rate of 30 bbl/min was attained. The well was opened up to the test unit and tested for 44.5 hr. The well exhibited a final rate of 18.9 MMCFD with 1648 psi FTP on a 64/64 choke. This production included approximately 32-bbl/hr water (Table 5).

Conclusions and Lessons Learned

Based on the data presented, the following conclusions can be drawn:

1. The ported-sub method worked well with the acid stimulation.
2. The reversible oil-based RDF cleaned up well, in addition, the solids-free reversible fluid exhibited no detrimental residuals.
3. The reversible oil-based RDF exhibited good rheological properties while drilling, however, extended periods out-of-the-hole resulted in deteriorating reversibility of the fluid system, whereby, additional treatment was necessary to maintain this property.
4. Losses were noted while running the ECP's and were most likely the result of disturbing the filter cake while running in hole.
5. This was the first application of a reversible invert-emulsion system in a high-temperature (>300°F) horizontal well drilled and completed in a carbonate reservoir in the Gulf of Mexico.
6. This well exhibited sustained initial production of approximately 15.88 MMCFG/D and 216 BW/D on a 32/64 choke as this rate was higher than anticipated.
7. Based on initial production and completion data, the reversible RDF solids-free system exhibited good stability using a 13.7-lb/gal $NaBr/CaBr_2$ internal phase. Initial produced fluids were emulsion-free and exhibited good phase separation.
8. The laboratory optimization testing for the 9.2-lb/gal reversible RDF solids-free system compared well with field application.

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Table 1
Petrophysical Data

		Carbonates:			Silica:	Clays:			Other:
Sample Depth	**Zone(s)**	**Calcite**	**Dolomite**	**Anhydrite**	**Quartz**	**Smetitic**	**Kaolinite**	**Chlorite**	**CEC**
5015									
5019									
5105									
5435									
5693									
15000-030		90	10	<1	-				<1
15030-040		16	81	<1	3	<1			3
15041	**Upper James**								
15051									
15065		98	2	-	<1				<1
15067 [1]									
15069 [1]		99	<1	<1	<1				
15150-184		94	4	2	<1				<1
15184-217		99	<1	<1	<1				<1
15217 [1]									
15222	**Lower James**	100	-	-	-				<1
15234									
15247		100	-	-	-				<1
15249									
15266									
15269									
15274		70	30	-	-				<1
15277 [1]									

1. Sample was analyzed using thin sections.

Table 2
Formulation of RDF Systems

Component	**Synthetic (IO_{16-18}-base)**	**Reversible (LVT-200-base)**	**Brine (Formate-base)**
Synthetic IO_{16-18}, lb	168.80		
LVT-200, lb		159.6	
Organoclay, lb		5.0	
$CaCl_2$, lb	25.05	48.8	
Organoclay, lb	5.0		
Lime, lb	3.0	12.0	
Primary Emulsifier, lb	8.0		
Secondary Emulsifier, lb	2.0		
Polymeric Fluid Loss, lb	2.0	1.25	
Fresh Water, lb	70.15	84.0	
VF Calcium Carbonate, lb	78.2	40.0	20.0
F Calcium Carbonate, lb	36.8	43.9	15.0
Viscosifier, lb			1.25
Fluid Loss Control Agent, lb			7.25
Anti-Oxidant, lb			2.0
Na/K Formate, lb			39.0
Rheological Modifier, lb		1.0	
Primary Emulsifier, lb		12.0	
Secondary Emulsifier, lbs.		3.0	

Table 3
Field Maintenance Worksheet

Potential Problem	Recommended Treatment *Maintain Reversibility of System*
High LGS ***(Target < 2 %)***	Dilute system at 10 – 40 bbl / 50 bbl. Isolate fresh Reversible pre-mix. Note: With carbonate formation not as critical
Drilling Shale Interval	Increase all system properties. Maintain reversibility Traditionally not a problem with OBM.
Sloughing Shale	Increase mud weight with calcium carbonate
High Reversibility ***(Target < 20)***	Treat with primary emulsifier at 1-3 lb/bbl and check LGS ***Pilot test and maintain excess lime at 3 lb/bbl***
Low ES Value ***(Target > 300)***	1. Treat with rheological modifier at 0.5 -1 lb/bbl 2. Treat with primary emulsifier and lime at 1-3 lb/bbl
Low Excess Lime ***(Target > 1.5 ppb)***	1. Treat with lime as needed
High Torque, Drag, or Poor Sliding	Increase all system properties. Maintain reversibility Traditionally not a problem with OBM
CO_2 & H_2S in System	Use LIME and maintain 3 lb/bbl excess LIME
Cement and Green Cement	Drill ahead. Traditionally not a problem with OBM.
Stuck Pipe	**Don't Pump Acid!** If differential, reduce hydrostatic. If cuttings, raise properties or spot base. Consider spotting base oil in open-hole
High PV	1. Dilute with unweighted pre-mix ***Pilot test*** 2. Dilute with diesel base and maintain target properties. ***Pilot test*** Check solids control equipment. If increasing run centrifuge
High Gels	1. Dilute with unweighted pre-mix ***Pilot test*** 2. Dilute with diesel base and maintain target properties. ***Pilot test***
Seawater or Formation Water contamination	1. Treat with pre-mix and add LIME as necessary as formation water is acidic. 2. Maintain target properties with lime, base oil, emulsifiers, dry $CaCl_2$
Increasing OWR	Add fresh water to maintain oil/water ratio
Low 6/3 Readings	1. Treat system with 0.5 ppb organoclay. 2. Treat with rheological modifier not to exceed 1 lb/bbl total in system
High HT Fluid Loss	Treat with polymeric fluid loss agent and rheological modifier Maintain reversibility
Water in HT	Treat rheological modifier Treat with conventional emulsifier
Seepage Losses	Sweep hole with 100-bbl pill with 50-lb/bbl Fine calcium carbonate. If loss persists, see moderate losses
Moderate Losses	Sweep hole with 100-bbl pill with 50-lb/bbl medium calcium carbonate. If loss persists, see severe losses.
Severe Loss Circulation	Pump 25 bbl pill of X-linked polymer plug. Requires saturated NaCl.

Table 4
Chemical Analysis of a Produced Fluid*

Property	Value
ES @ 120°F	8
Reversibility, mL acid	15
Oil, vol %	4.5
Water, vol %	92
Solids, vol %	3.5
Estimated OWR	5/95

* As noted on morning report 7/18/03

Table 5
Initial Production Data*

Date	Tubing Pressure (psi)	Choke	Gas Production (MMCFD)	Water Production (BPH)	Note
7/16	1151	48	5.47	27.0	Before acid
7/17	3116	32	12.74	Not reported	After acid
	2630	42	14.85	35.9	
7/18	1648	68	18.88	32.0	
7/24	3039	32	15.88	216 BW/D	30-45 ppm H_2S

* Data from field reports of 7/16/03 to 7/24/03.

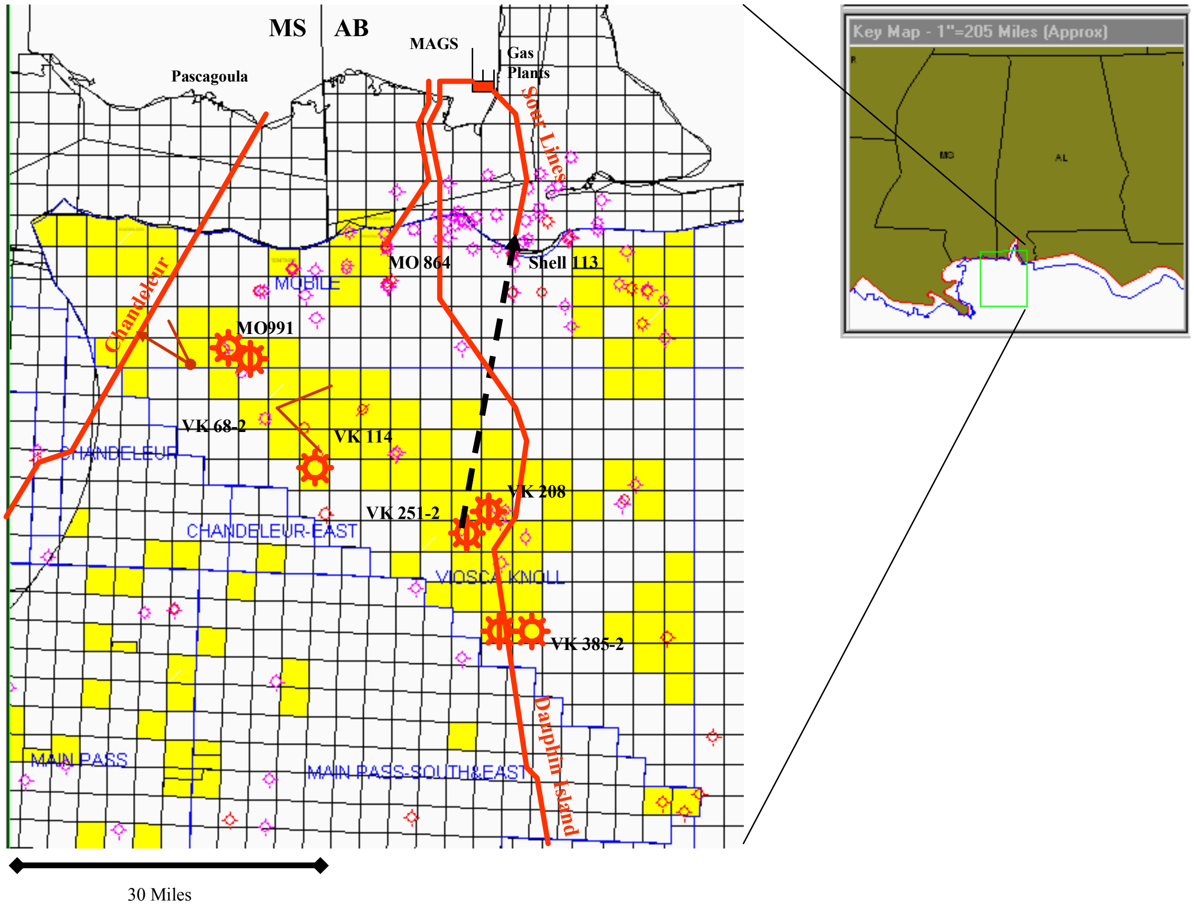

Fig. 1 – Offshore Mississippi and Alabama areas showing deep wells > 14,700 ft. TVD and pipeline gathering system.

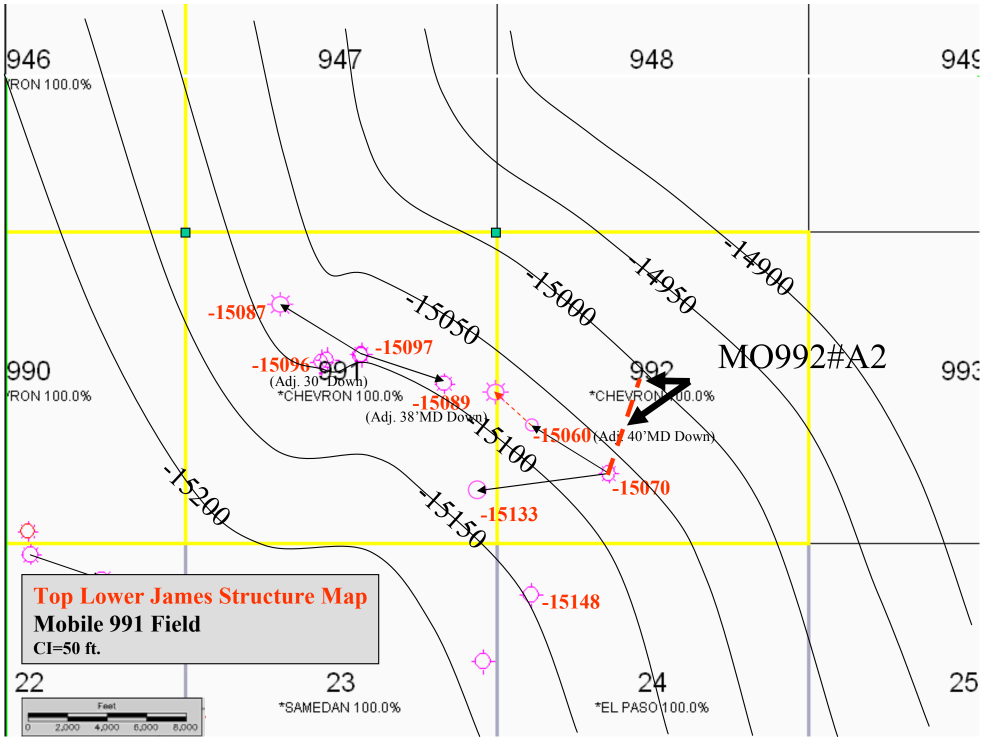

Fig. 2 – Offshore Alabama showing Mobile and Viosca Knoll areas and approximate subsea depths of the Lower James

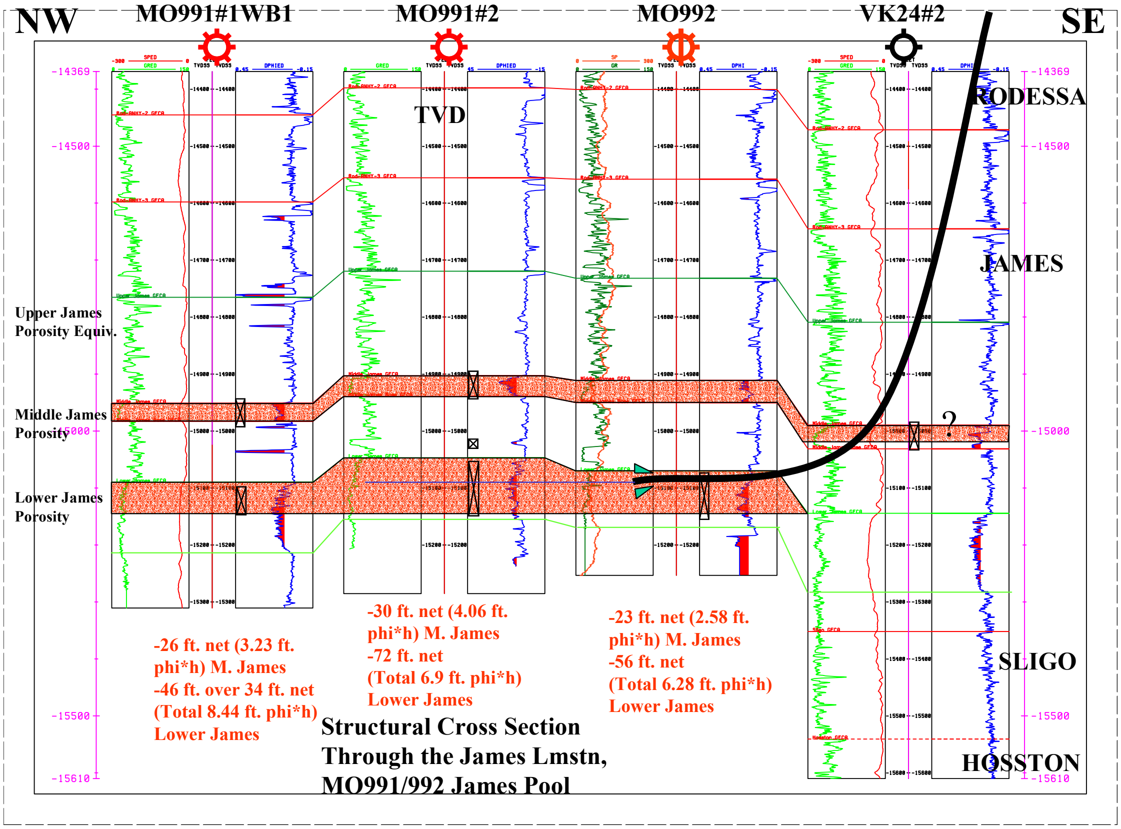

Fig. 3 – Structural Cross Section through the James Limestone

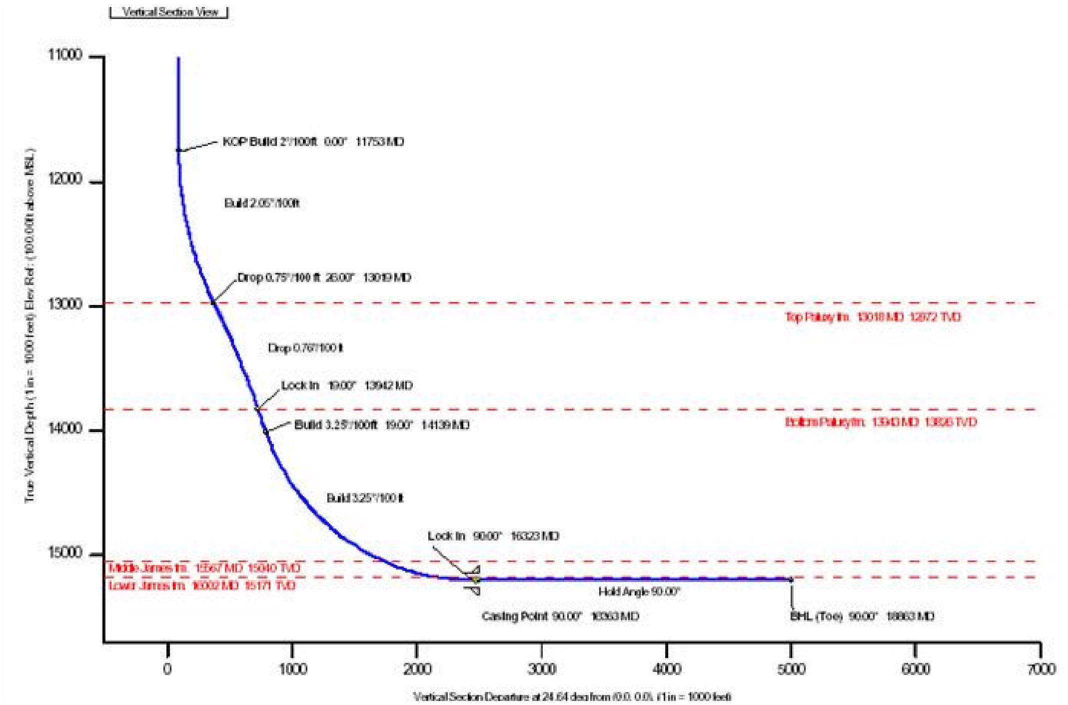

Fig. 4 – Proposed Directional Plot

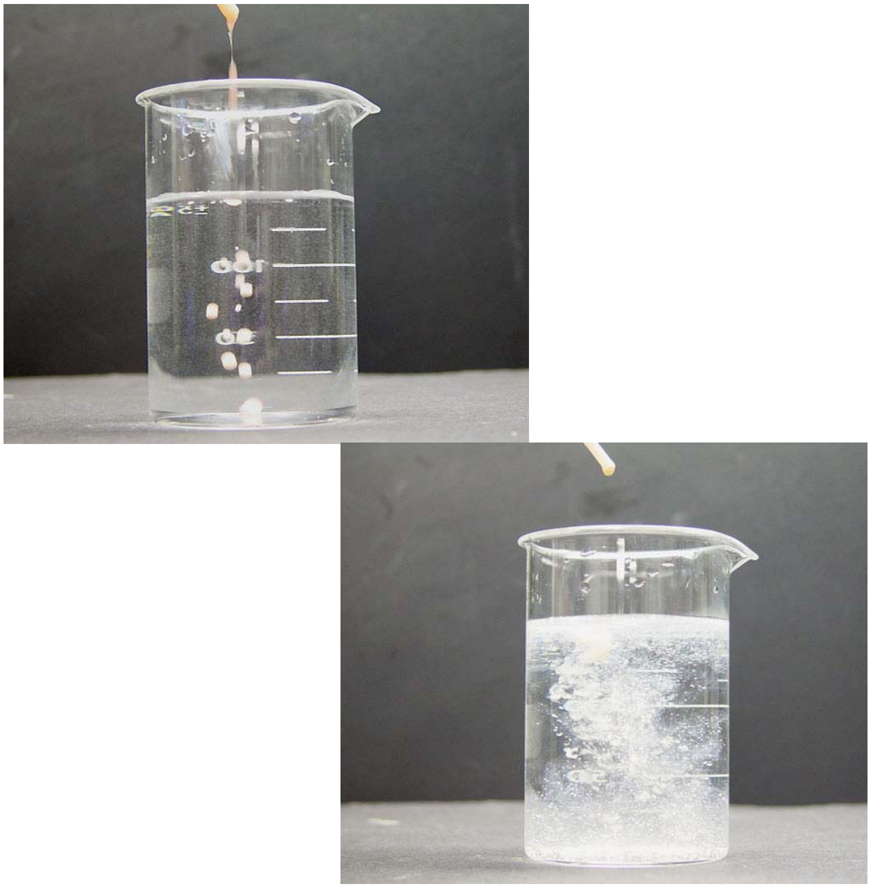

Fig. 5 – Digital images exhibiting reversibility of a 9.4-lb/gal Reversible Solids-Free. Image in upper left shows Reversible Solids-Free retains its oil-wet state in fresh water as droplets remain spherical. After contact with 15%HCl acid, the Reversible Solids-Free disperses readily in water, an indication the system has reversed to a water-wet state, lower right.

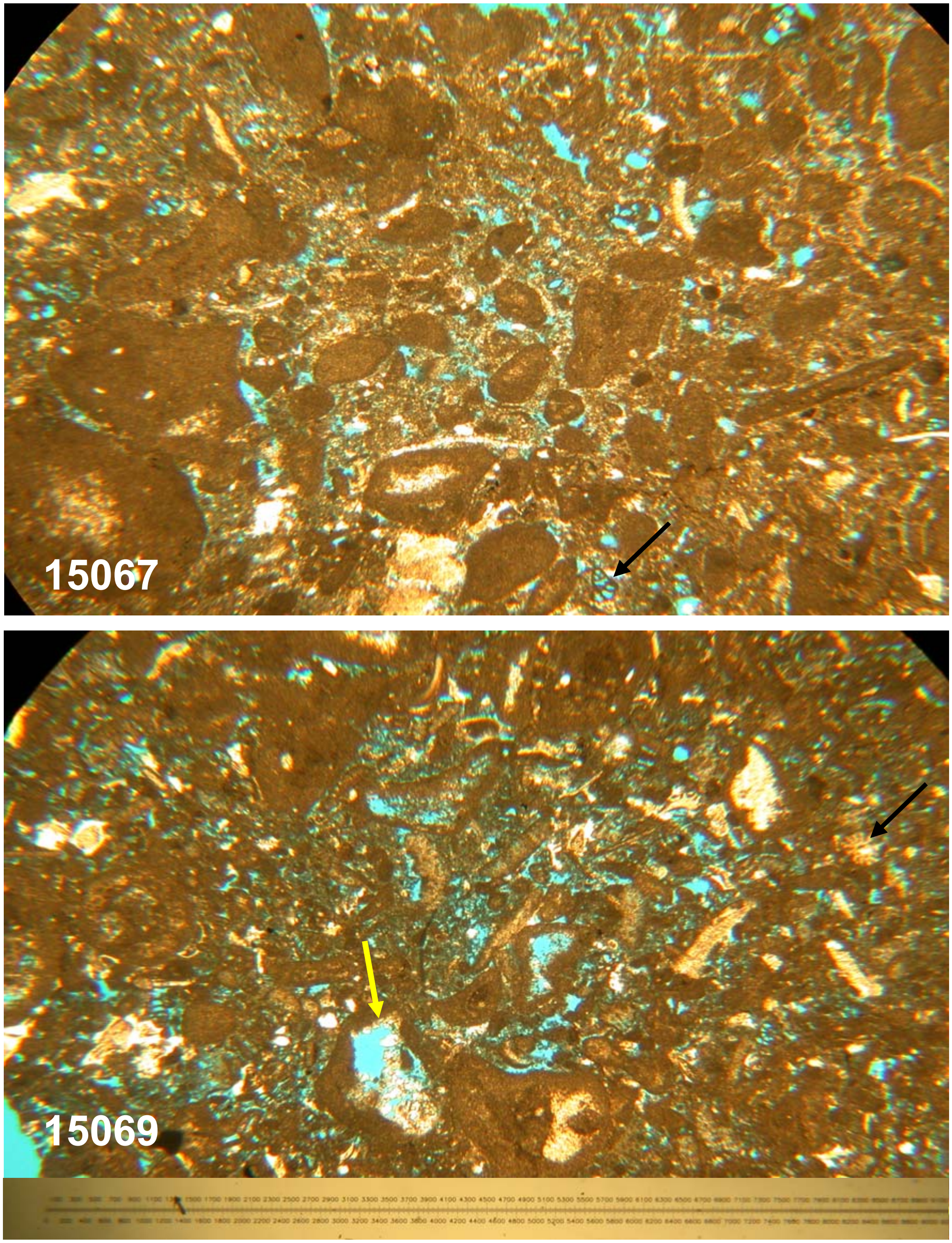

Fig. 6 - Thin section micrographs of samples collected from 15,067 and 15,069 ft. Isolated pores are ubiquitous and are often lined with calcite rhombs (arrow). Dissolution of fossil has created secondary pores (arrow-top photo). The lined-pore in the lower-left exhibits dimensions of approximately 300 microns x 500 microns

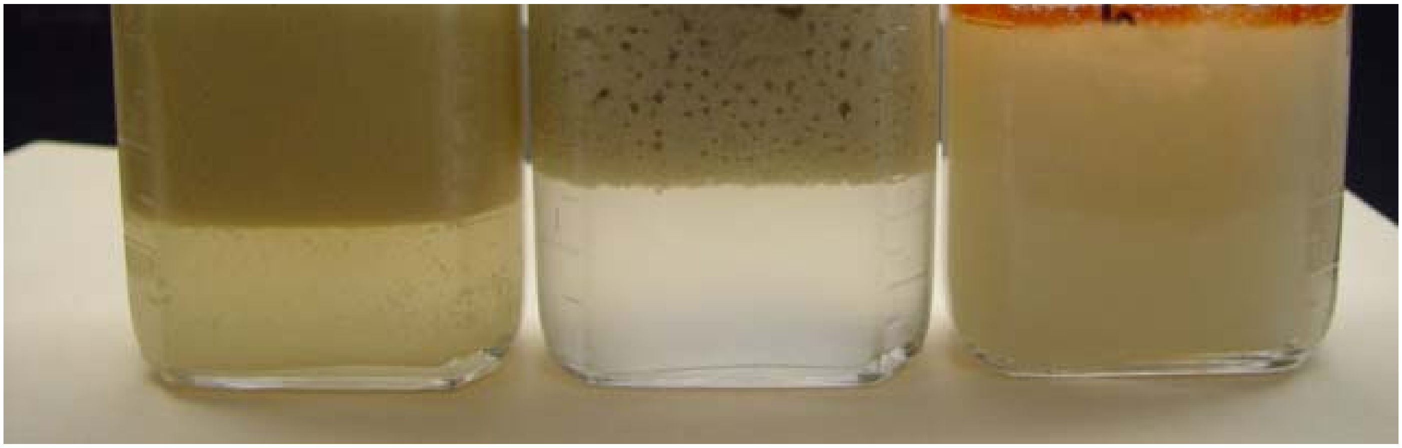

Fig. 7 – Comparison between three RDF systems and an acid clean-up system after static aging. Left to right: SBM, reversible-OBM, and WBM.

Fig. 8 – Digital images of a compatibility test of a 13.7-lb/gal NaBr/$CaBr_2$ blend. This blend was heated to 300°F for 6 hours and then cooled rapidly. Turbidity after cooling was approximately 3 NTU.

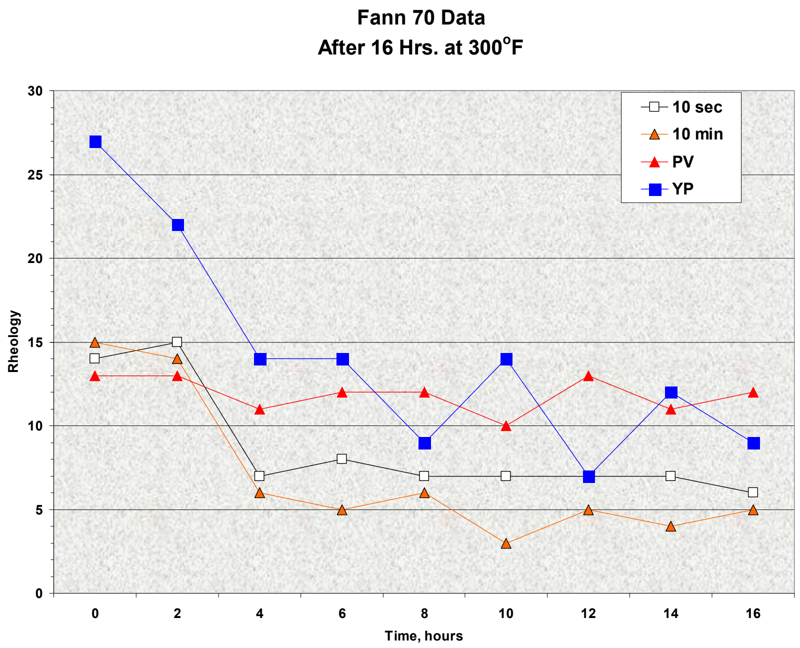

Fig. 9 – Fann 70 data of a 9.2-lb/gal Reversible SF system 100 at 300°F. The cell paddle was alternated every two hours from static mode to dynamic mode (stirring at 300 rpm).

Fig. 10 – Residual reversible-RDF filter-cake (top) after simulated flowback. Residual SBM-RDF filter cake (bottom) after simulated flowback.

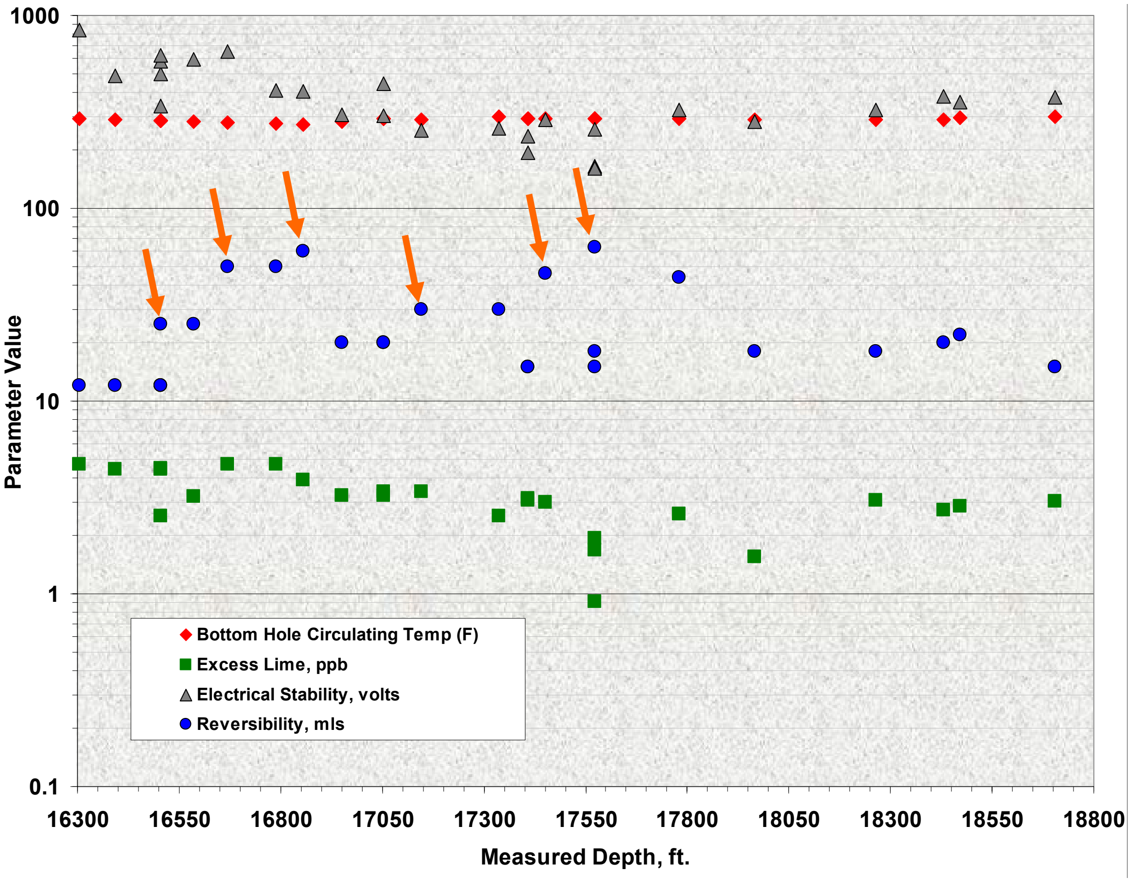

Fig. 11 – Selected Reversible system and wellbore parameters collected while drilling the lateral. Arrows indicate a trip for bit change, tool failure, or logging run.

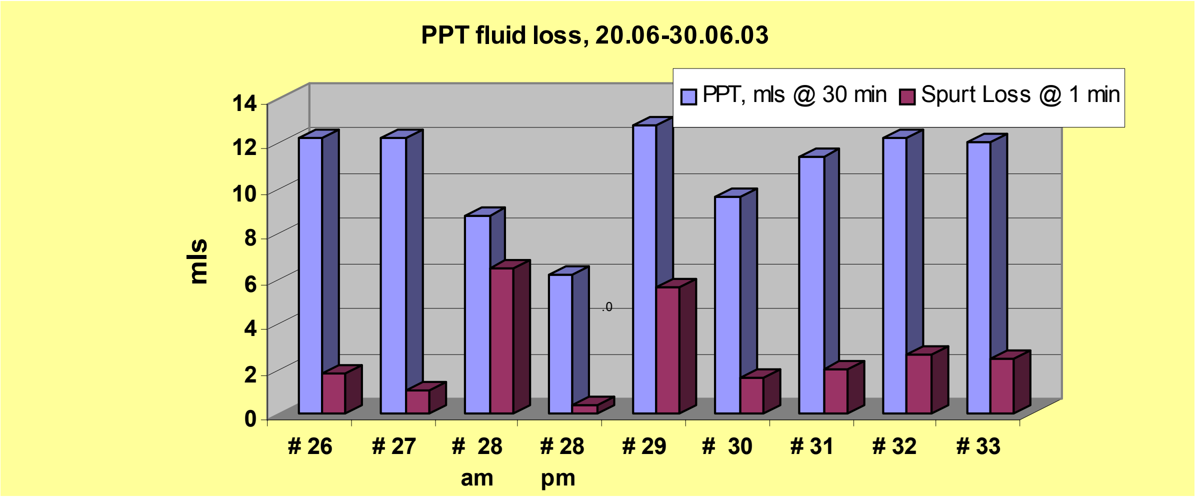

Fig. 12 - Field PPA data for the reversible-RDF using 1000 psi differential pressure at 300°F.

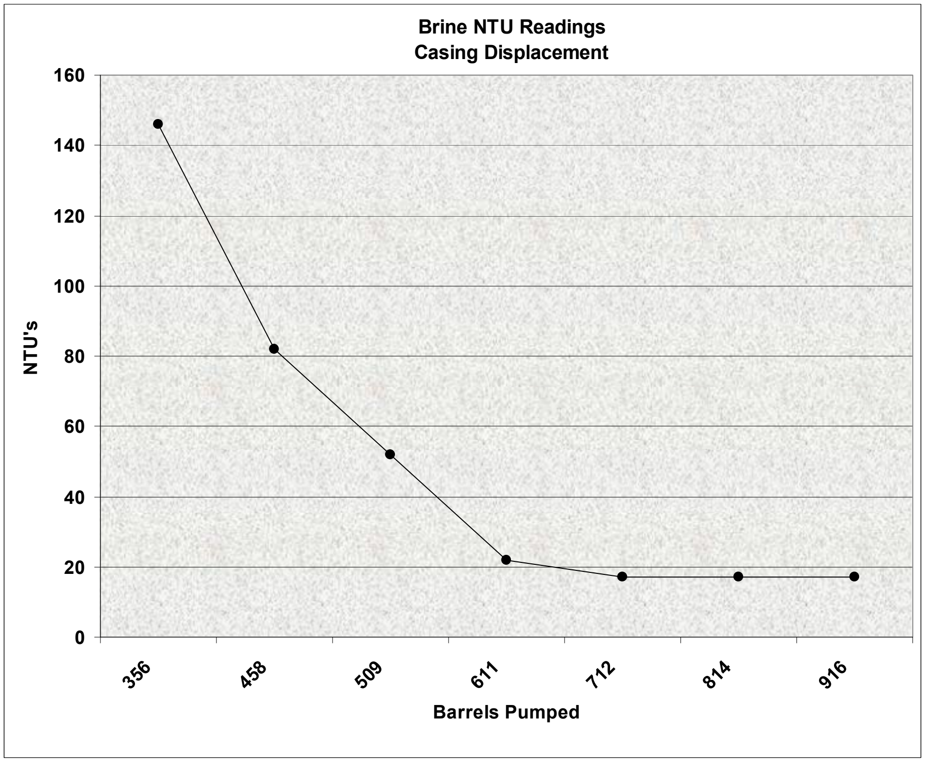

Fig. 13 – Measured clarity of the 9.2-lb/gal NaBr completion brine after displacing the 7-in. casing from Reversible Fluid to NaBr.

Fig. 14 – Produced fluid sample (right-side) from the initial flowing of the well. This sample was collected after stimulation with acid.