SPE 144205-PP

Field Experience from a Biotechnology Approach to Water Flood Improvement

B.G. Bauer, R.J. O'Dell, Merit Energy Company, S.A. Marinello, J. Babcock, T. Ishoey, Glori Oil Limited, E. Sunde, Statoil S.A.

This paper was prepared for presentation at the SPE Enhanced Oil Recovery Conference held in Kuala Lumpur, Malaysia, 19–21 July 2011.

Abstract

This paper is based on a field implementation in the United States of a biological process for improving waterflood performance. The Activated Environment for Recovery Optimization ("AERO™") System is being developed by Glori in collaboration with Statoil and derives its roots from a microbial enhanced oil recovery technology developed and successfully implemented by Statoil offshore Norway. Unique among IOR technologies, AERO implementation requires virtually no capital investment and achieves high performance efficiencies at low operational cost. The simplicity of setup allows pilot project implementation creating a very low risk entry point for the operator.

A pilot project was selected for a controlled investigation of the performance and impact. Robust testing was done in both water and oil phases prior to treatment, confirming the potential for improved sweep and conformance from the project. Subsequent implementation resulted in decreased water cut and increased oil recovery observable both at the wellhead and allocated pilot levels.

This paper summarizes a rigorous analysis of the pilot project's performance to date, concluding that the production improvement should be credited to the implementation of the AERO™ System.

Introduction

An AERO™ (Activated Environment for Recovery Optimization) System field pilot was initiated at the Stirrup Field in southwest Kansas (Figure 1) to evaluate the potential improvement in recovery from a waterflooded reservoir. The field is at a relatively mature stage of waterflood and following robust testing of the water and oil phases, it was believed that the AERO™ System could enhance performance through improved sweep and conformance.

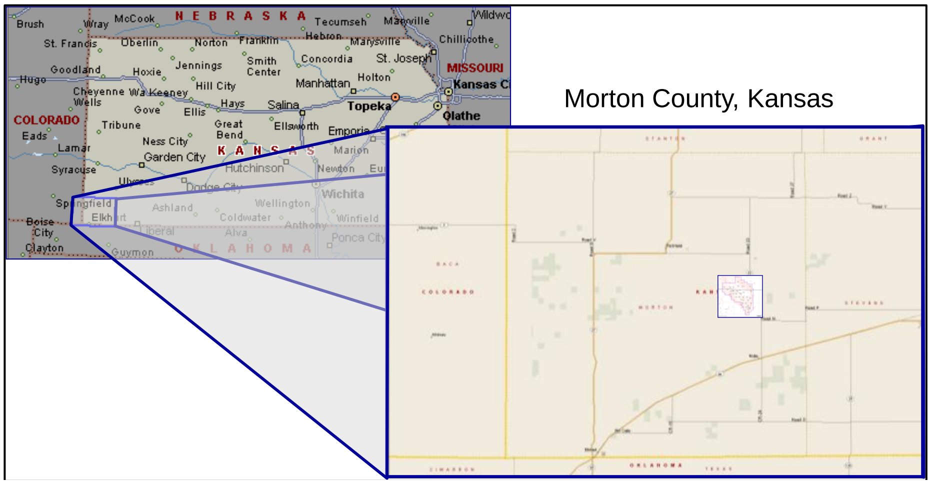


Figure 1: Location Overview for the Stirrup Field

The Stirrup Upper Morrow ‘D’ reservoir is a sandstone with a moderately to poorly sorted matrix deposited in a paleo valley system encased in marine shales and located at a depth of 5,200 feet. The average net pay is 20 feet, with porosity estimated at 15% and permeability at approximately 75 mD. The reservoir was discovered in 1985, with first production and initial development coming from the gas cap. The oil column was not encountered until 1989. Further delineation established that the Morrow ‘D’ reservoir contains a very large gas cap relative to the size of the oil column[1]. Conflicting interests among the field’s operators precluded attempts to implement allowables or put in place a reservoir management plan. This resulted in primary production that focused on blowing down the gas cap, which ultimately impaired oil recovery. When secondary recovery was finally implemented in 2003, reservoir pressure had declined from its initial value of 1,650 psi to less than 100 psi across the field. This necessitated a more unique approach at waterflooding, whereby the majority of injection wells were arranged in a curtain near the gas/oil contact, as shown in Figure 2. The produced oil gravity has been between 38^o and 41^{o}API. Following gas cap production and limited primary oil production, the estimated recovery was only 13% of an estimated OOIP of 19.123 million barrels. Secondary recovery is forecast to yield an additional 2.75 million barrels, for a EUR of approximately 27% of OOIP.

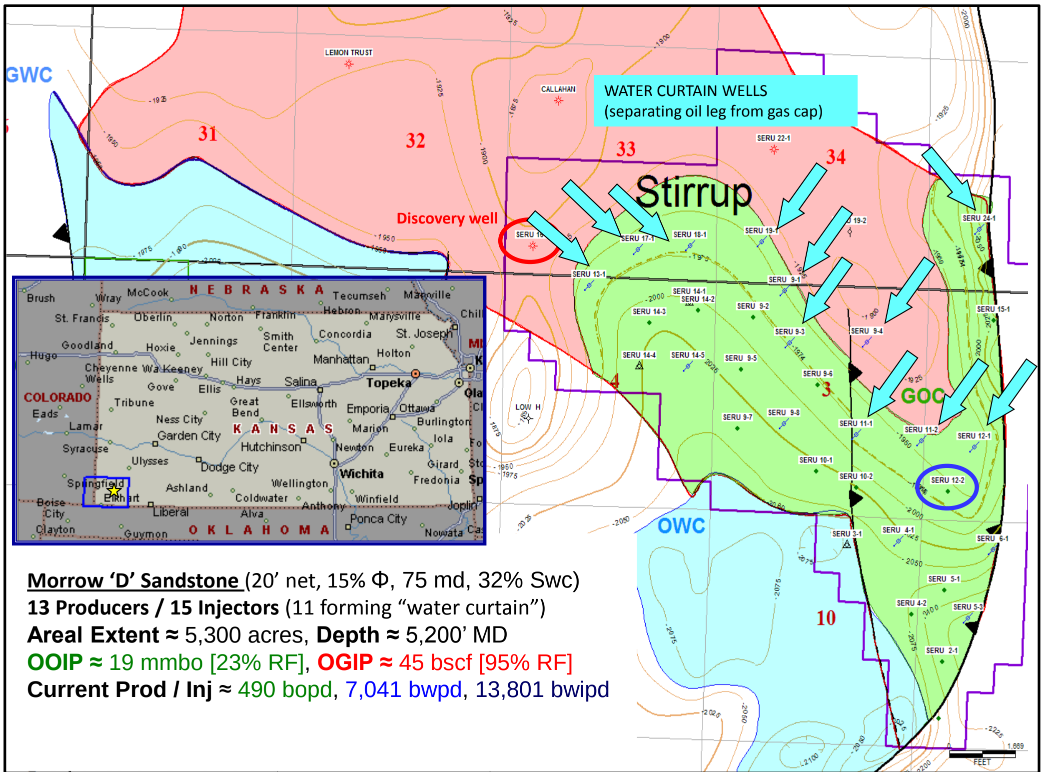


Figure 2: Stirrup Enhanced Recovery Unit w/ Water Curtain Wells Noted

The Stirrup AERO™ System pilot was initiated in May 2010. A broad-based bacterial inoculant and a specifically tailored nutrient package were initially injected, with supplemental tailored nutrient injection to support development during the course of the pilot. The project was applied to an irregular pattern, initially with two injectors and five producing wells being sampled. It was anticipated that communication would develop along a dominant path between the injectors and a primary producer, driven by existing flow paths and differential pressure conditions.

Field implementation resulted in improved recovery and water cut in the pilot area, but injected fluid volumetric limitations and subsurface heterogeneity resulted in the pattern being restructured and the removal of an injector and a producer from the active pattern. The justification for this change is summarized in a subsequent section. Although it did not take place during the period focused on in this paper, another producing well was converted to an injector First Quarter 2011. Before considering expansion into other areas of the field, an engineering evaluation was performed to ascertain any contributing impacts from other potential factors that might affect observed incrementals and other aspects of the pilot’s performance.

Background

Biotechnology or Microbial EOR can be defined as the application of biological processes to facilitate, increase, or extend oil production from a reservoir. As with all EOR processes, the goal is to improve recovery performance by mobilizing oil left behind by primary production mechanisms, or secondary water flooding operations. This is an old concept, with pilot tests dating back to the 1950's and considerable activity and research directed to the topic during the late 1970's and early 1980's. The body of research and pilots performed resulted in a fair amount of literature, but skepticism about the mechanisms of the processes and implementation of the technology led to limited consideration or adoption within the industry. Part of this has been due to the fact that it is a complex process spanning multiple disciplines, as well as disparity in field performance compared to laboratory results; a fairly common issue with EOR technologies. Some mixed results in practice would appear to be poor field implementation and/or project design, which may be attributable to an incomplete understanding of how microbial activity might affect oil recovery mechanisms. Advances in microbiology in the last decade have led to a revised interpretation of these historical approaches and facilitated the birth of a new generation of biotechnology applied to improve oil recovery[2].

The AERO™ System has been developed to improve waterflood performance and increase recovery via a combination of mechanisms dominated by two specific processes:

- Improved sweep efficiency due to micro diversion of fluid pathways at the pore level
- Interfacial tension reduction & residual oil mobilization via surfactant-like behavior of microorganisms.

As was noted earlier, it was anticipated that microbial processes would develop along a dominant path between the injectors and a primary producer, driven by existing flow paths and differential pressure conditions. Sweep alteration and residual oil mobilization were the expected mechanisms for the Stirrup pilot.

Baseline Waterflood Performance Evaluation

In order to evaluate the performance of the AERO™ System pilot, it was necessary to ascertain the actual performance and mechanics of the ongoing waterflood across the Stirrup Field prior to project initiation. The implementation of 'water curtain' injection wells focused on the gas/oil contact in order to isolate the depleted gas cap from the oil zone. This resulted in the (anticipated) loss of the majority of injected water from these wells into the gas cap. In order to be able to assess the real impact of the AERO™ System on oil and water production from the wells included in the pilot, an accurate estimate of the actual injection and withdrawal associated with the pattern's pore volume under the existing waterflood operation had to be determined. In performing a field level evaluation, a better understanding of the displacement dynamics in and adjacent to the pilot was obtained.

Industry accepted techniques for waterflood evaluation were used to establish well allocation factors on injectors and producers for the purposes of pattern analysis[3]. These factors were optimized by using the resultant allocated production & injection volumes in fill-up calculations, which were tied back to actual waterflood response as shown in rate-time, Jordan, and Staggs plots. Figures 3 and 4 show the disparity between the total injected volume and the apparent water volume

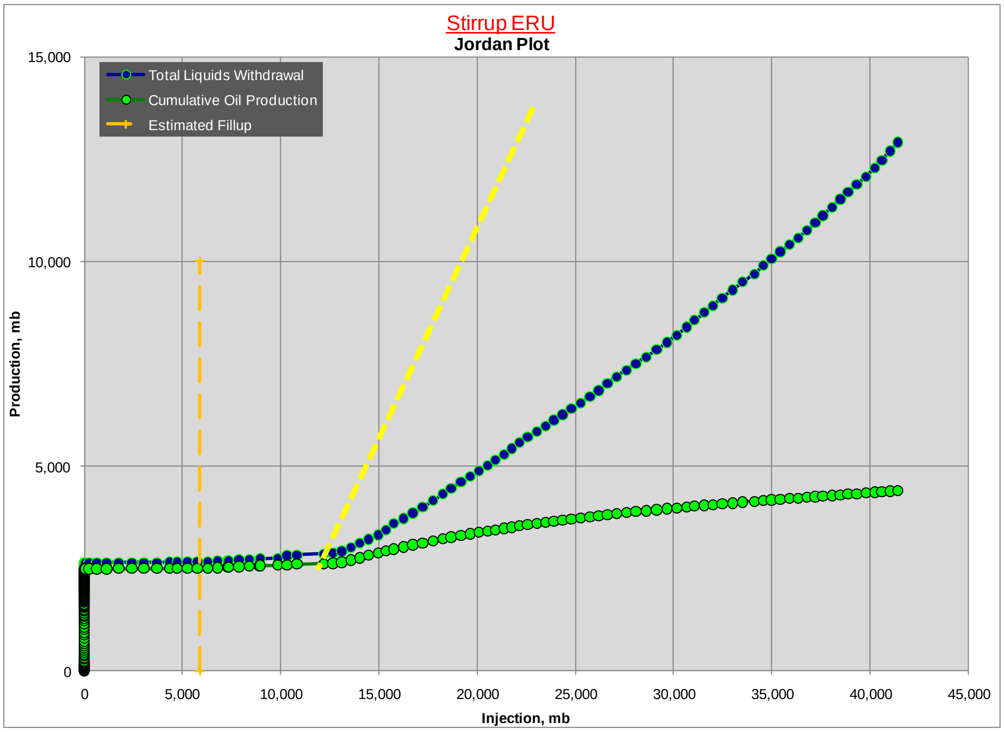


Figure 3: Disparity between Calculated and Actual Fill-up

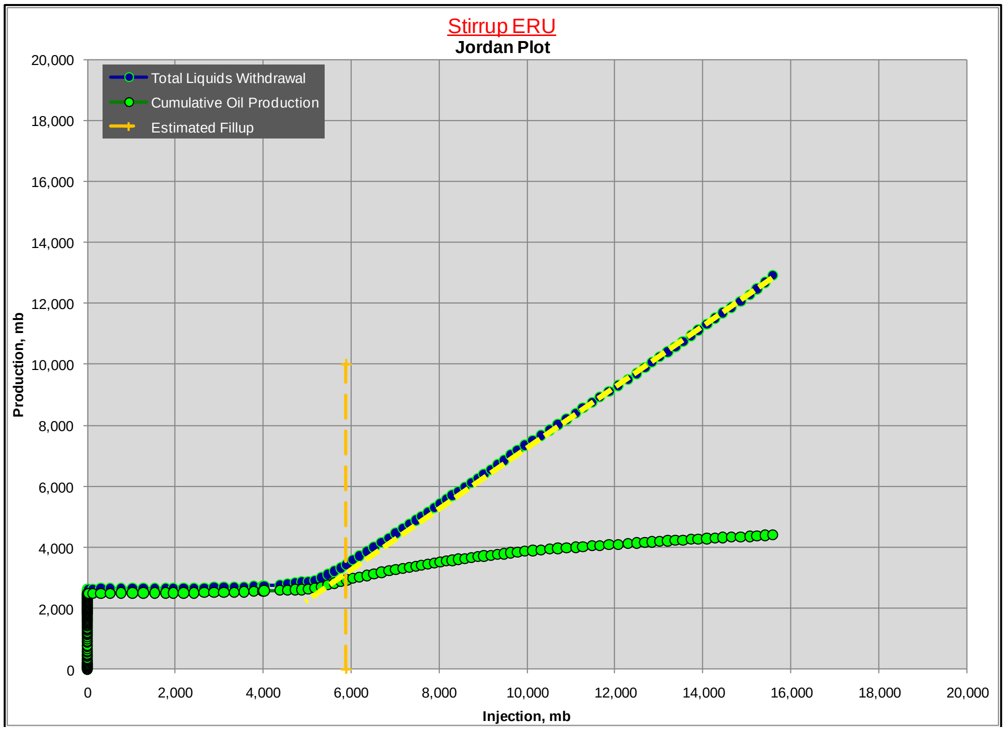


Figure 4: Reduction in Applied WAF's Provide Consistency with Withdrawal Data

entering the field. Adjustments to the well allocation factors were made to match the performance history for water withdrawal and oil production prior to the onset of the AERO™ System pilot.

Well Performance Evaluation

The economics of a mature waterflood on a field the size of Stirrup make the implementation of EOR techniques difficult due to the capital investment required by most methodologies. The objective of the pilot was to show that the AERO™ System could be implemented with minimal capital investment and successfully increase oil production and anticipated ultimate recovery. A re-evaluation of waterflood performance was performed after the early results of the AERO™ System pilot had been reviewed. It was apparent that the volume of injected water entering the pilot pattern was less than that required to provide sweep. This affected the ongoing pilot and field operations as water was reduced to certain injectors. As a consequence, some producing wells were subsequently designated for conversion to injectors.

The pattern utilized in the SERU (Stirrup Enhanced Recovery Unit) AERO™ System pilot was designated 4-1, as it is centered on the SERU 4-1 injection well (Figure 5). Two injectors were initially inoculated on May 20, 2010; SERU 4-1 and SERU 5-3. Pilot production was monitored at SERU wells 2-1, 4-2, 5-1, 10-1, 10-2, and 12-2. After several months of operation, it became apparent that SERU 5-3 was not actually operating as part of the test pattern; the water injected there was not entering the pilot area. This determination was based on an analysis of injection and withdrawal in the eastern portion of the field. In short, the total withdrawal from nearby producers did not nearly equate to the volume of water injected into the 5-3 and the inclusion of this well in fillup calculations prevented any semblance of a history match to actual data as shown in waterflood analysis plots. Further evaluation of three-dimensional seismic data shows that this well bisects the easternmost fault. It is likely that injection into this well is being lost through this fault. Therefore, SERU 5-3 was removed from the pilot analysis. It became apparent, with this realization, that the pilot area was not receiving sufficient water injcetoin from SERU 4-1 to achieve the sweep potential envisioned in the original design.

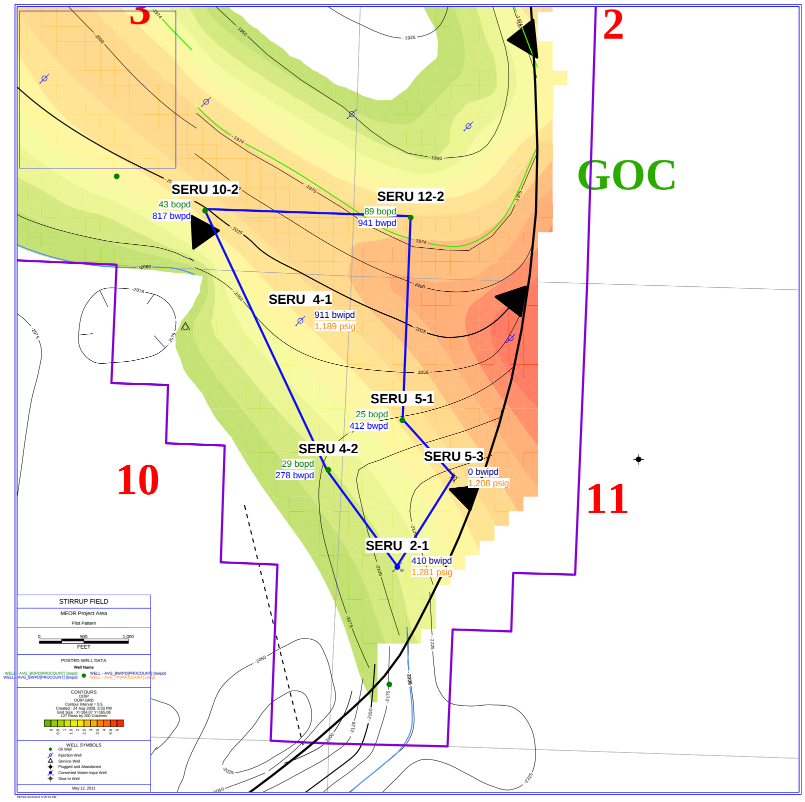


Figure 5: Injection Pattern 4-1 Pilot Configuration with Updated Well Status

SERU 12-2, located northeast of the 4-1 injection well, was the only producer to show a markedly positive production response. It exhibited a significant increase in oil production three and a half weeks following initiation of the pilot. Production increased as much as 200%, and then fell to a rate corresponding to a 60% increase going forward. The stabilized rate is greater than the 2009 average. Water production was elevated for the first period and followed the same pattern. However, water production did not increase by the same factor as the oil, more closely paralleling the change in total produced volume. As such, the approximate water cut decreased. The 12-2 well had seen an increase in both oil and water production following a pump change two months prior to project initiation. Water cut had decreased following the exchange of the pump, decreasing to approximately 88%, but had begun to increase just prior to pilot initiation. It was approximately 91% at the onset. Water cut then fell significantly to a level as low as 85% during the period of greatest production increase. By May 2011, water cut had returned to 91%.

Based on proximity to the 4-1 injection well, incremental oil was first anticipated to show up at SERU 5-1. However, production from 5-1 actually decreased slightly after initiation, although there was a short period of increased production in June 2010. Production fell slightly more after that time and then remained relatively stable until mid-January 2011. At that point, production again increased for a couple of weeks, but fell thereafter. These variations are, again, likely due to transient diversions in water support. As they do not seem to be related to injection in 4-1, it raises the question as to how much support is coming from the pilot injector. The well does not appear to be damaged, which may indicate that the permeability in the area towards the edge of the structure is tighter than elsewhere.

It had been expected that the most significant impact of the pilot would be felt in the path generated between the injector and the producer with the lowest potential; that is, with either the lowest bottomhole pressure and/or the flow path of least resistance. Preferential flow direction is based on the differential pressure between two points and the mobility between them, which is function of permeability, or relative permeability, and effective viscosity, which combines to provide resistance or ease of flow along a particular path. Fluid will always follow the path of least resistance. The answer to why the greatest impact was felt at SERU 12-2 may be attributed to the path of least resistance having been established during waterflood operations. The communication paths from 4-1 to the 12-2 and 5-1 wells are roughly orthogonal to each other. A review of the regional stress data shows that the direction of maximum stress runs SW-NE. This parallels the path between SERU 4-1 and SERU 12-2. During waterflood operations, it is possible, or likely, that some limited fracture was initiated between the two wells. That initial path would be sufficient to have flow preferentially move towards 12-2. Once established, diversion of flow and/or release and activation of residual oil would take place more readily along the interfaces along the path.

Mindful of these issues, producer SERU 2-1, which had not exhibited significant impact during the pilot, was taken off line during mid-March of 2011, and converted to an injector. Although its position relative to SERU 5-1 is not exactly parallel to the stress direction, the situation is notably better than SERU 5-3 and as it adds critical volume to the pilot injection area, there may be an increased likelihood that a flow path will be established between the two wells.

SERU 2-1 production had not changed in the first five months of the pilot. Oil production increased suddenly and erratically in September 2010, with water production increasing as well, while the water cut, which had been trending upward, fell back slightly to 96%. Oil production returned to earlier levels within weeks, but water production increased and the water cut went back up; from roughly 96% to almost 98%.

Oil production decreased at SERU 4-2 shortly after initiation, which would suggest that there was some diversion of water support from its drainage area at that time, with transient variations causing the minor production increases in February and April of 2011, while water production remained stable.

SERU 10-1 saw a reduction of water production in late 2010 and into 2011, with an oil production increase in February. These results did not correlate with the 4-1 pattern and it was later determined that 10-1 was on the western side of an apparently sealing fault, isolated from the pilot pattern. SERU 10-2 had seen a short term increase in oil production shortly after the pilot was started, with relatively stable water production. The responses seem to indicate some communication with injectors other than, or in addition to, 4-1.

The fluid production variations for the non-responding wells have not been of magnitudes significantly different from typical operating ranges. There have been a number of divergent impacts on the various producing wells, but they do not necessarily show any interdependent relationships. It would be hard to characterize such interdependencies given the distances and time delays. The lack of dependent responses indicates that the inoculant and nutrients did not get established along communication paths with the 4-1 injector.

AERO™ System Pilot Performance Evaluation

Because the gathering and allocation for the pilot area is tied up in the field system and Stirrup lacks a highly accurate dedicated testing system or individual separation, an evaluation can only be made on relative performance on a well by well basis. Un-controllable well events and injectivity changes in other areas of the field appear to have masked many of the positive effects of the pilot program. However, the favorable results seen within the pilot are quite encouraging.

As noted, the overwhelming majority of the total pilot response was at SERU 12-2. It is felt that, through this period, insufficient water was entering the 4-1 pattern to impact any other wells. Subsequent follow-up work suggests that the other production wells within the pattern have been predominantly influenced by adjacent injectors due to these volumetric limitations. Therefore, the performance improvement observed, with consideration of various operational upsets, was almost entirely due to the result of the oil mobilized between SERU 4-1 and SERU 12-2. Figure 6 presents the production history for the 4-1 injection pattern through the end of 2010. The uptick in production corresponding to the response of the SERU 12-2 is clear.

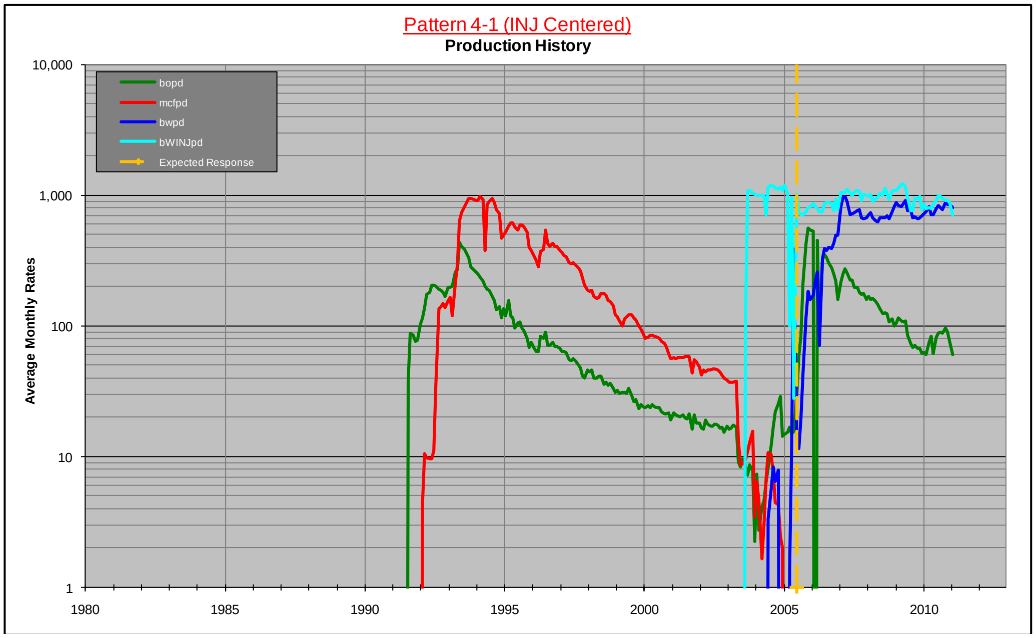


Figure 6: Injection Pattern 4-1 Production History

Figure 7 presents a plot of oil cut vs. cumulative recovery, providing for comparative predictions of waterflood and BEOR recovery. For the extended period of the pilot, while production did increase at 12-2, it did not fall off significantly in the rest of the modified pattern. The production and recovery data are shown again in a classic rate-time plot in Figure 8, in which the estimated recovery from primary, secondary, and BEOR implementations are shown to be 20.2%, 42.7% and 45.9% respectively for the injection pattern. That estimate is for the complete injection pattern volume, but it is believed that only a fraction of that volume, specifically the volume related to SERU 12-2, is being swept, due to the prevalent well relationships established during waterflooding, as well as because of insufficient water being injected into the pattern. Assuming that the pattern volume associated with 12-2 is approximately 25% to 35% of the total, the incremental recovery from the impacted volume is estimated to be between 9% and 12%. However, the true swept area between these two wells is unknown, and further work is required to resolve the improvement to sweep efficiency and corresponding incremental benefit. Further work & extension of the pilot is planned. This modification and expansion has and will focus on providing sufficient injection volumes and on improving the sweep in the targeted areas.

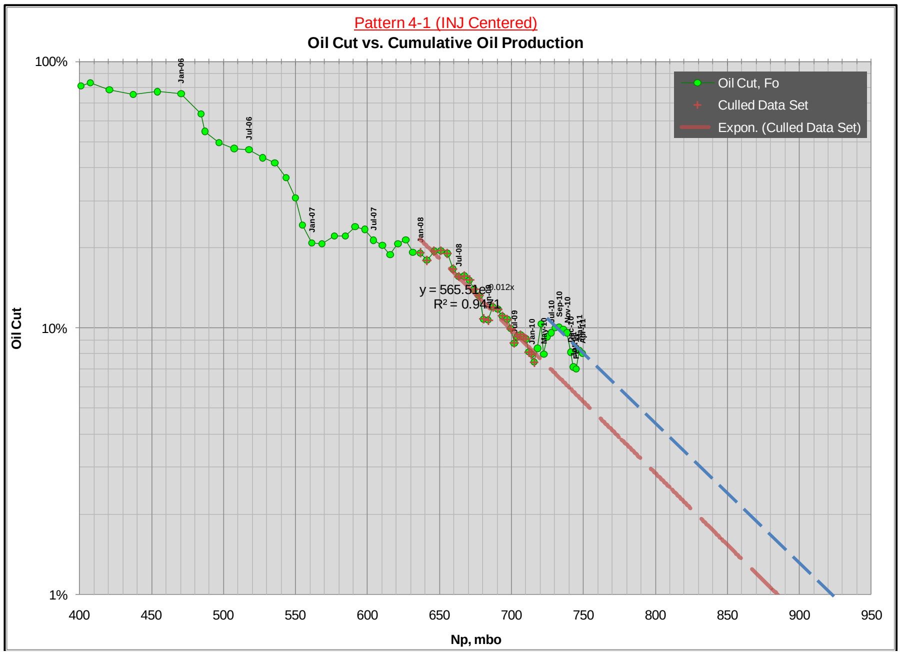


Figure 7: Pattern 4-1 Oil Cut vs. Cumulative Oil Recovery Factor

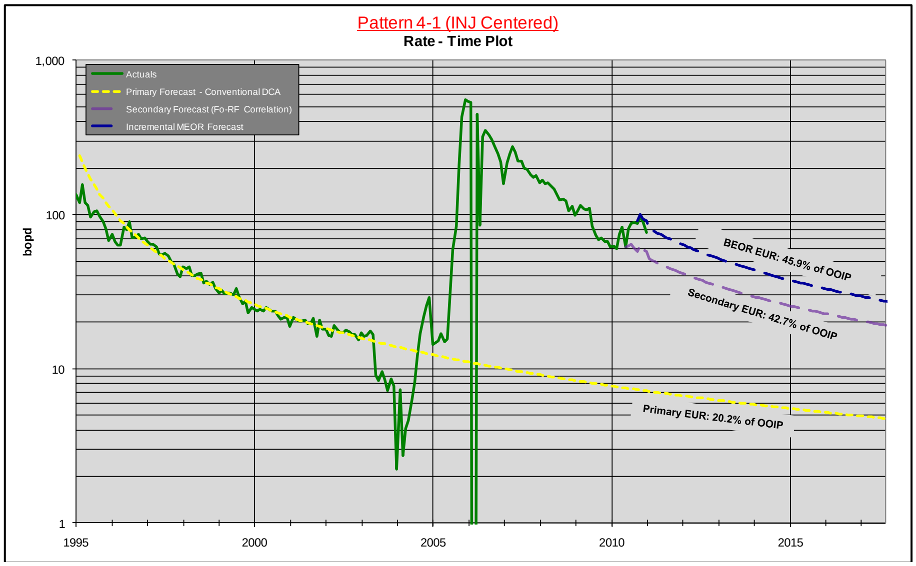


Figure 8: Pattern 4-1 Production Forecasts –EUR for Primary, Secondary and BEOR

Focusing on the SERU 12-2 well alone and analyzing well test data, Figure 9 compares oil cut to oil production over the life of the well. Trend extensions for waterflood and AERO™ recovery at the oil cut limit suggest 40 mbo of incremental oil over the life of the well. Note that the short term deviation prior to the end of the year was from a field allocation effect;

production during that period was essentially unchanged. Figure 10 plots water cut vs. oil production and shows that there was a significant reduction in water cut during the initial peak incremental production period of the pilot. Water cut at the end of the year had nearly returned to pre-pilot levels, which would tend to suggest banking of the oil along the path between wells.

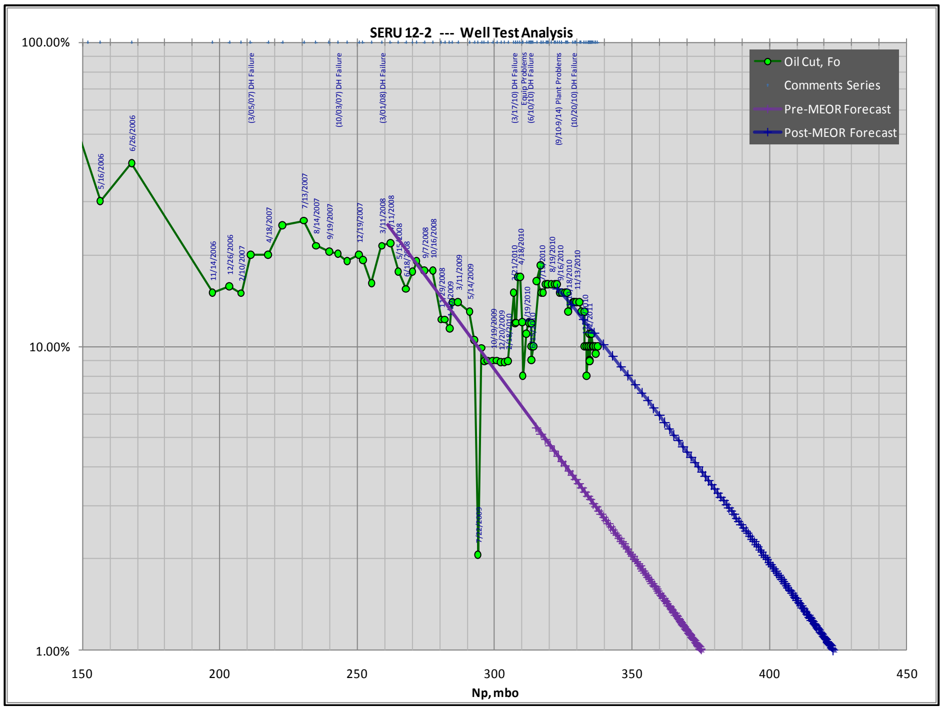


Figure 9: SERU 12-2 Oil Cut vs. Np – Waterflood and BEOR Projections

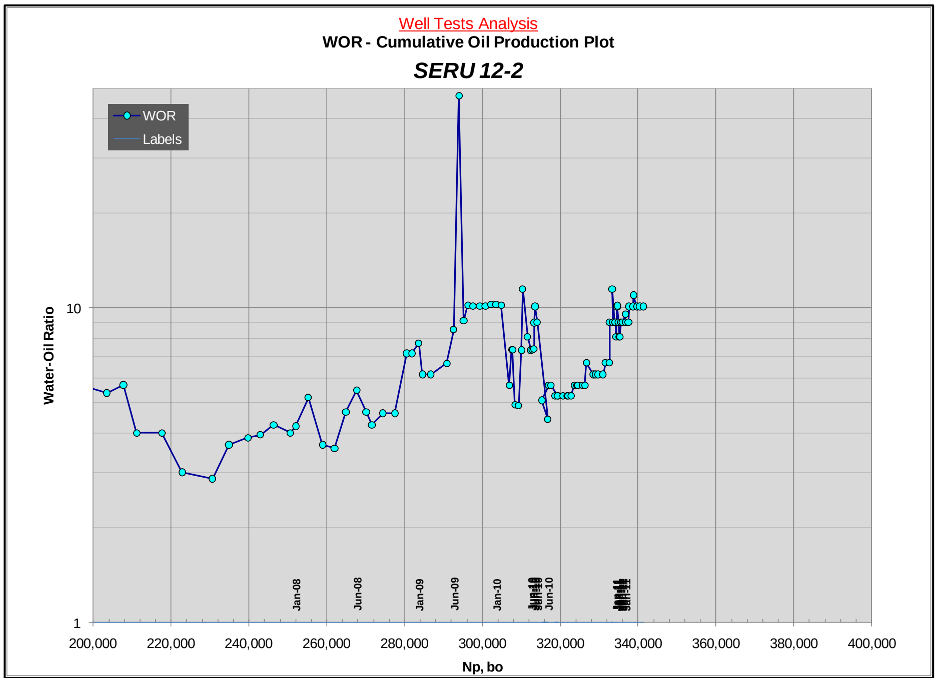


Figure 10: SERU 12-2 WOR vs. Np

Oil and water production are both plotted against time in Figure 11, clearly indicating the incremental production when the mobilized oil arrived at the well. Projections indicate estimated decline trends for both waterflooded and AERO™ cases. As shown in Figure 12, which plots oil production rate vs. cumulative production, it is estimated that 17,604 bbls of incremental production were recovered from SERU 12-2 by years end. Oil production has fallen by over half since the peak monthly rate in June 2010, but it is still approximately double the expected rate prior to the onset of the pilot and pump upgrades.

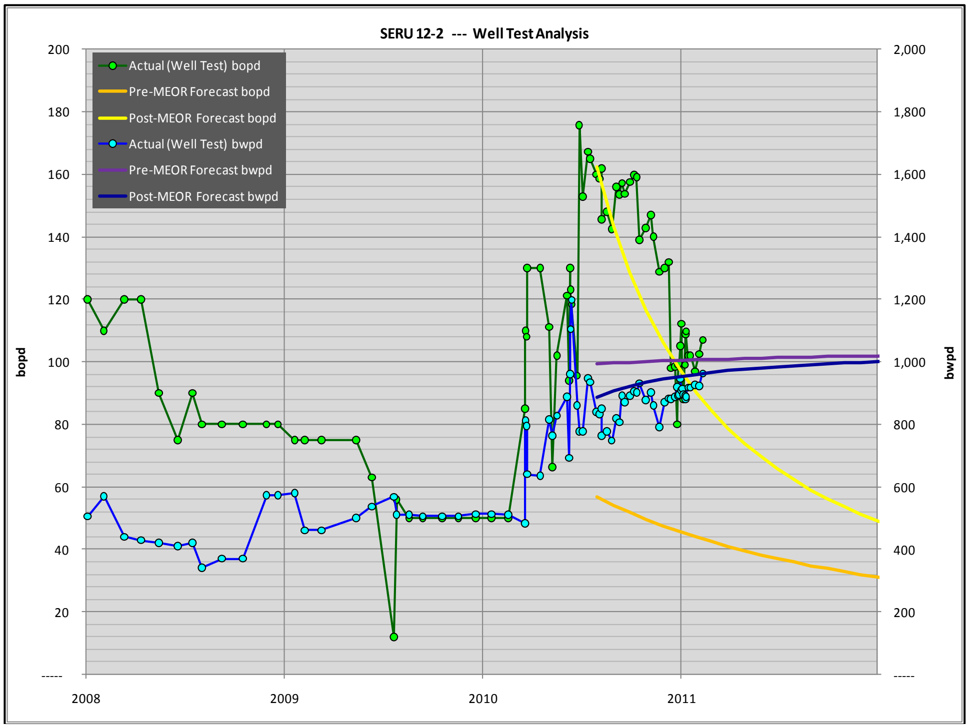
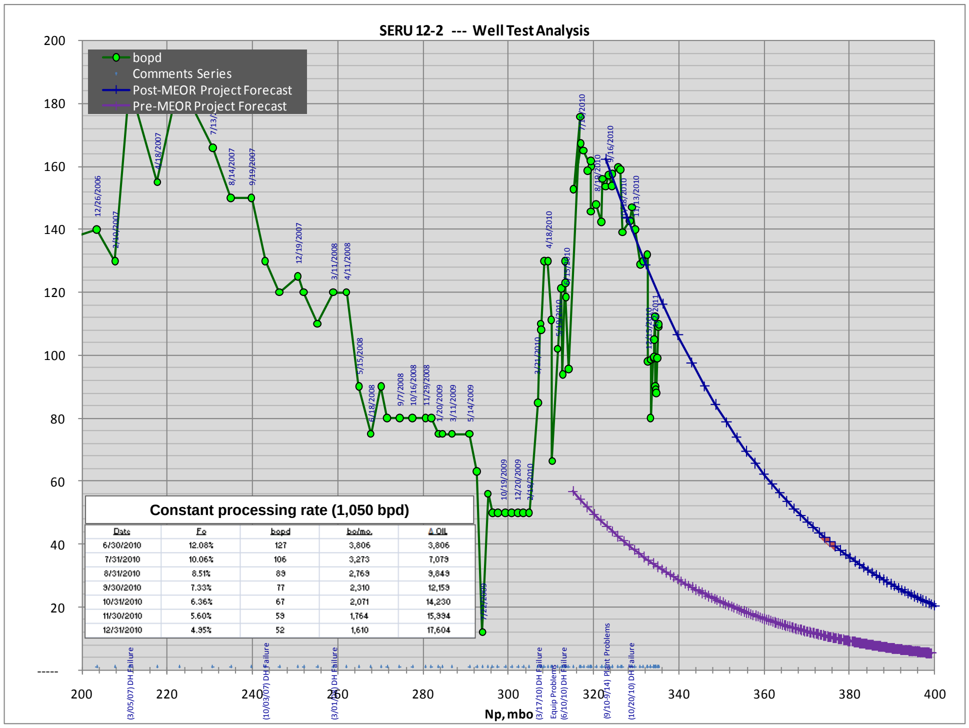


Figure 11: SERU 12-2 Oil and Water Production Rate Histories and Forecasts



Constant processing rate (1,050 bpd)

Date	Fo	bopd	bo/mo.	Δ OIL
6/30/2010	12.08%	127	3,806	3,806
7/31/2010	10.06%	106	3,273	7,079
8/31/2010	8.51%	89	2,769	9,849
9/30/2010	7.33%	77	2,310	12,159
10/31/2010	6.36%	67	2,071	14,230
11/30/2010	5.60%	59	1,764	15,994
12/31/2010	4.95%	52	1,610	17,604

Figure 12: SERU 12-2 Oil Production History and Forecasts

Summary

The Stirrup AERO™ System Pilot was implemented to determine if incremental oil could be recovered from a reservoir at a mature waterflood stage. The pilot was based on certain premises and expectations, some of which occurred, and some that didn't. Anticipated production from SERU 5-1 did not materialize, but further evaluation of waterflood pattern response and stress orientation in the field suggested that there would have been preferential flow between the SERU 4-1 injector and the SERU 12-2 producer, which is what has occurred during the course of the pilot to this point. In evaluating the allocated contribution of water injection to the 4-1 injection pattern and considering the pilot performance, which was dominated by the 12-2 well, it was estimated that 3.2% additional incremental oil would be recovered from the pattern pore volume by the end of operations, if they continued as originally implemented. Analysis showed, however, that the pattern was not receiving sufficient water to allow coverage and that the incremental oil was recovered from only 25% to 35% of that pore volume, which translates into a 9% to 12% incremental recovery from the pilot application if the given volumetric assumptions are correct.

Steps were implemented in early 2011 to improve water supplied to the pattern, with the conversion of the SERU 2-1 producer to an injection well. Expansion of the pilot to the larger part of the field is also being planned, and consideration of the possible impact of stress orientation and existing communication paths will impact the design and expectations of that effort.

References

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