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Horizontal & Directional Drilling

Short-Radius Rotary Steerable Drilling Key To Enhancing Recovery In Horizontal Waterflood

Part Three

Horizontal Waterflooding

Enhances Oil Recovery In Shallow, Low-Permeability Bartlesville Sandstone

By R.V. "Bob" Westermark, Scott Robinowitz, Dwight Dauben and Helen Virginia "Ginny" Weyland

TULSA–Supported by a grant from the Department of Energy, Grand Resources Inc. has implemented a project to test horizontal waterflooding using short-radius rotary steerable and underbalanced drilling techniques to improve oil recovery in the shallow Bartlesville reservoir in Osage County in northeastern Oklahoma.

Reservoir screening is the first step in the process, and then rock mechanics are used to predict well bore stability for determining the most efficient completion method. Geologic and reservoir parameters are considered in selecting the radius of curvature for the horizontal well and the air/foam drilling fluids used to avoid formation damage. The final step is to run a comprehensive set of logs through the curve and into the reservoir for petrophysical evaluation.

Grand Resources' Osage County project sought to meet three primary goals:

- Demonstrate the technical and economic feasibility of using horizontal waterflooding to recover additional oil in shallow, low-permeability reservoirs;
- Demonstrate the viability of open-hole completions techniques based on well bore stability considerations; and
- Demonstrate that short-radius rotary steerable technology can drill horizontal wells at low cost and without reservoir damage.

Significant amounts of oil typically remain trapped in the producing formation when wells in waterflooded fields are abandoned because of high water-to-oil ratios (WORs), causing production to be uneconomical. Many techniques have been developed to more economically recover this bypassed oil. The technique employed by Grand Resources uses parallel horizontal water injection and production wells to enhance oil recovery.

The Bartlesville reservoir in northeastern Oklahoma has been one of the most prolific oil-producing formations in the United States, and it remains an important producing horizon even though it is considered to be in a mature stage of depletion. In spite of large cumulative production from the Bartlesville, recovery efficiency has been low–usually less than 20 percent of the original oil in place. Recovery during primary production operations is low as a result of a solution gas-drive mechanism that leads to rapid pressure depletion, and low initial reservoir pressure that is a consequence of the shallow depth.

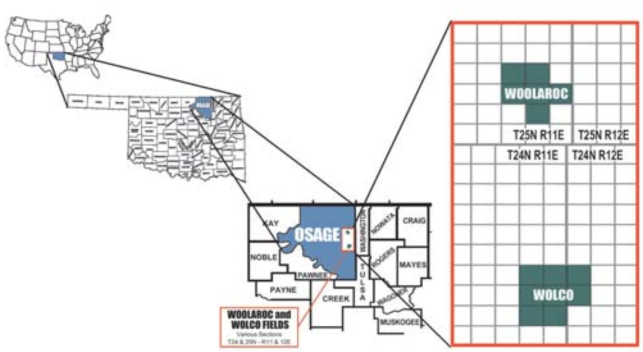
Enhanced Recovery Operations

Not surprisingly, the remaining 80 percent of the OOIP has attracted many secondary and tertiary recovery projects. However, secondary recovery operations are often not effective or economic because of shallow reservoir depth, the existence of natural fractures, and the low permeability. The Bartlesville sandstone across Osage County ranges in depth from 1,000 to 3,000 feet, and is naturally fractured with permeability values typically less than 50 milliDarcies (mD).

In an attempt to improve the economics of Bartlesville waterfloods, operators frequently inject water above the fracture-parting pressure to achieve better injectivity. The results are often unfavorable, since water tends to channel through the fractures and bypass much of the remaining oil in the matrix. Developing small flood patterns with closer well spacing can lead to improved recovery, but the large number of required wells negatively impacts the economics.

FIGURE 1

Location of Horizontal Waterflood Pilot Test Area



Although horizontal waterflooding has been successfully demonstrated in several field projects, most applications have been focused on deeper reservoirs (4,500 feet or deeper) where horizontal wells can save money by replacing the need for multiple vertical wells. The application of horizontal injection and producing wells in shallow, low-permeability reservoirs is an area of opportunity for horizontal technology. In a previous DOE-supported project, an operator had attempted to use a horizontal injection well to overcome the injectivity limitations of the Red Fork Formation (the geologic equivalent of the Bartlesville) in a pilot area of the Glenn Pool Field south of Tulsa. Unfortunately, that horizontal well was not completed because of mechanical difficulties.

Horizontal wells can be expensive as a result of drilling techniques that typically increase completion costs. Using mud as the drilling fluid is a serious problem in all wells, but especially those drilled in low-permeability and low-pressure reservoirs. To remediate drilling mud invasion into the formation, expensive completion techniques are often required to remove mud filtrate damage from the near-well bore region and establish contact with the reservoir's natural permeability. These completion techniques can also destabilize the well bore, requiring a liner to be set, which further increases well costs.

The key issues in the correct application of horizontal well technology pivots around achieving desired productivity/injectivity of the wells and the cost associated with drilling the horizontal wells without damaging depleted, low-pressure reservoirs.

Osage County project

Horizontal waterflooding, as applied in the Osage County project, consists of one horizontal injection well and two adjacent parallel horizontal producing wells that straddle the injector. The basic concept is that large volumes of water can be injected at pressures below the fracture parting pressure of the reservoir, with the horizontal producing wells, in turn, capturing the oil that has been mobilized. By contrast, conventional waterflooding is often not effective in shallow, low-permeability reservoirs like the Bartlesville sandstone because of the inability to establish adequate injectivity below the fracture parting pressure. Fracture parting pressure is often exceeded, resulting in injection water channeling and bypassed reserves.

The project sought to demonstrate the economic impact of horizontal waterflooding in an area adjacent to an existing vertical waterflood. Initially, the project team concentrated on collecting data for a pilot in the Woolaroc Field (Figure 1). Reservoir description studies were conducted to identify a suitable unflooded area within the field for a pilot test area. A vertical well was drilled in the pilot area to collect additional data, including well logs and cores. The plan was to plug back after data collection and drill a horizontal lateral into the reservoir.

The core collected during this process indicated that the reservoir was relatively uniform in properties and contained a significant amount of oil, but permeability was unexpectedly low. Simulation studies using core permeability values indicated that horizontal waterflooding would improve performance over conventional waterflooding, but not to a sufficient degree to be economically successful.

A suitable test site was identified in the nearby Wolco Field (Figure 1). The Wolco is adjacent to the North Avant Field, an abandoned 1980s-era waterflood. The Wolco Field was redrilled in the 1980s, but not subjected to waterflooding activities. In

FIGURE 2

Producing Rates for Vertical and Horizontal Waterfloods (23-Acre Spacing)

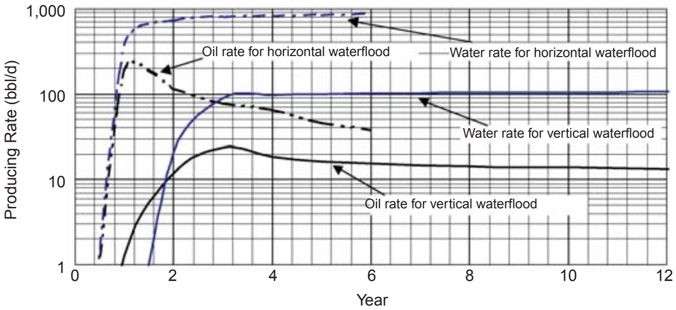
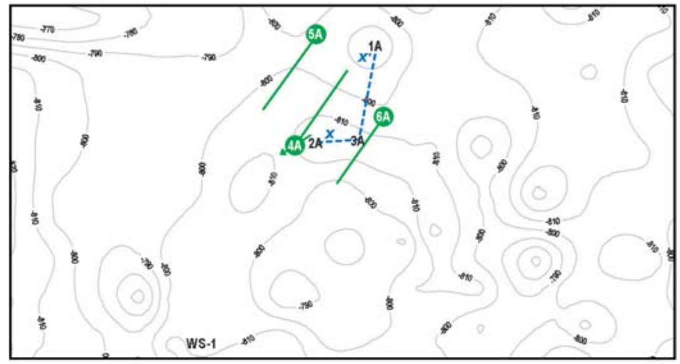


FIGURE 3

Structure Map of Bartlesville Sandstone in Pilot Test Area (Scale: 1 inch = 1,000 feet)



the pilot test area, there are three existing wells in the quarter section, the Wolco Nos. 1A, 2A and 3A. A shut-in water supply well in the adjacent quarter section to the southwest was available for the horizontal waterflood pilot.

Simulation studies were conducted to confirm the suitability of the Wolco site and the optimum placement of wells. The Bartlesville sandstone at the site has a thickness of ±85 feet, porosity in the range of 16-20 percent, and estimated permeability is 30-100 mD. Based on simulation studies, the horizontal injection well was planned to be drilled 20 feet from the bottom of the sand and the two producing wells were to be drilled 20 feet from the top of the sand.

Figure 2 shows the results of a simulation performed in the pilot area. It indicated that high injection and producing rates could be maintained during the life of the project. Moreover, the oil could be recovered quickly, which would be highly beneficial in achieving an economic operation. However, the WOR would increase, which had to be considered in designing and installing the surface production facilities.

Drilling Plan

Figure 3 is a structure map of the pilot test area, showing the location of the existing wells and the three pilot area wells drilled parallel to the suspected prevailing fracture orientation within the field. Alignment with the expected fracture orientation was planned as a precaution in the event that open fractures were encountered. In that case, good sweep efficiency could still be maintained while injecting water to displace oil toward the adjacent horizontal producing wells. Figure 4 is a cross-section drawn through the existing wells showing the top and bottom of the Bartlesville formation, with an upward dip of 1.5 degrees to the northeast.

Cost-effective drilling operations are the cornerstone of this horizontal waterflooding program. Open-hole completions provide the least expensive method of completing the wells into the Bartlesville sandstone. Rock mechanic studies indicate that the matrix of this Pennsylvanian Formation has the strength and competency allowing for open-hole completions.

Directional drilling was accomplished using a proven rotary drilling system that consists of two drilling assemblies, a curve drilling assembly (CDA) and lateral drilling assembly. The CDA drills a very predicable curve of a designed turning radius based on tool configuration. These wells were drilled with the CDA configured to drill a 70-foot radius curve (the well path goes from vertical to horizontal following a curve scribed by a 70-foot radius.) By drilling 110 feet measured depth, the inclination increased from zero (vertical) to 90 degrees (horizontal).

The CDA was then removed from the well and the lateral drilling assembly was run in to drill the desired horizontal section of the well. Using the Wolco No. 4A as an example of the short-radius underbalanced drilling technique, the vertical portion of the well was drilled to a total depth of 1,628 feet. Open-hole logs (gamma ray, induction and a sonic-based bore hole televiewer) were then run to confirm geology and identify fracture existence and orientation. No fractures were identified during this logging run.

At that point, 5½-inch production casing was run to 1,627 feet and cement was circulated to the surface. The CDA was picked up and run into the well. A gyroscopic surveying tool was utilized to orient the CDA. The 70-foot radius curve was drilled from 1,635 to 1,733 feet MD. The curve maintained the desired direction and ended as planned, which allowed the lateral section to be drilled parallel to a slightly updip formation. The curve was drilled using water as the circulating medium.

Underbalanced Drilling

The lateral section was drilled underbalanced, circulating with air/foam to minimize formation damage in the low-pressured reservoir. Two different lateral drilling assemblies were used for drilling the horizontal section of the well. A modified air hammer bottom-hole assembly was first run in the well, but a correction run was necessary because the air hammer assembly was dropping angle too quickly. After the correction run, a packed-hole rotary drilling system was used, with frequent surveys taken to check for proper well bore direction and inclination. The packed bottom-hole assembly held the desired inclination angle and direction. The Wolco No. 4A was drilled to a final measured depth of 2,732 feet.

A directional plot of the No. 4A well is shown in Figure 5. It presents the well plan and the actual well bore path based on survey results. The drilling of the Wolco No. 4A followed the plan regarding direction, inclination and total length drilled.

Grand Resources has developed a method to log horizontal wells through short-radius curves by deploying logging tools via sucker rods. The gamma ray, density, induction and bore hole televiewer logs were run to determine fluid saturations, identify fractures and confirm geology through the horizontal section of the 4A well. Logs were run into the horizontal sec-

FIGURE 4

Cross-Section of Bartlesville Sandstone in Pilot Test Area

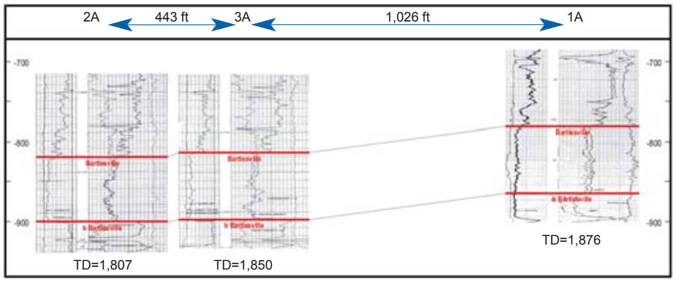
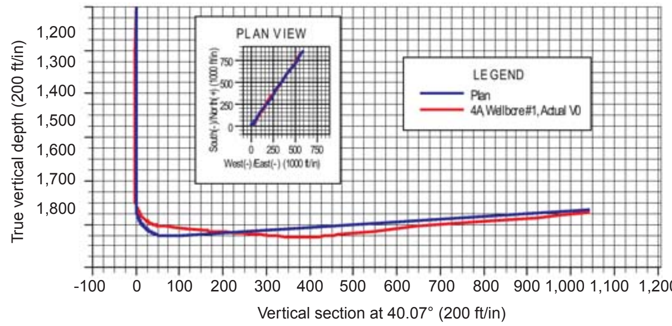


FIGURE 5

Directional Plots for Wolco No. 4A



tion of the well bore approximately 500 feet. After logging 500 feet of lateral section, friction and the flexibility of the sucker rods prevented the logs from going any farther. To overcome the distance limitation of the sucker-rod conveyed logging technique, work is now progressing to adapt a commercial downhole wireline tractor to pull the logs out into the lateral section through the short 70-foot radius curves.

The bore hole televiewer log was run from 1,626 to 2,248 feet. This log is designed to detect and interpret fracture existence and orientation. It encountered very few fractures in the well bore. The density log was run through the lateral from 1,732 to 2,245 feet and porosity values averaged 16 percent. The induction log was run through the curve and 550 feet into the lateral portion of the well. Resistivity values in the top section of the Bartlesville (1,650-1,700 feet measured depth) were approximately 5 ohms. Resistivity values along the length of the lateral (1,732-2,270 feet) averaged 2 ohms. Low resistivity values were expected in the well bore because of its position near the bottom of the reservoir.

Drilling, Production Results

After drilling the No. 4A well, the No. 6A and then 5A Bartlesville Sandstone horizontal wells were drilled in the Wolco Field. A continuous improvement process of well planning, drilling and post-well review was applied to learn lessons from each well drilled. The technique resulted in each successive well being drilled more efficiently and more cost-effectively than the previous well. The first well drilled, the Wolco 4A, cost $257,000. The second well, the Wolco 6A, cost $214,000, and the third well, the Wolco 5A, cost $202,000. By comparison, the average cost to drill and complete a typical vertical well in the Bartlesville in the Wolco Field was estimated at $98,000.

Simulation results, coupled with an economic evaluation, indicate a horizontal waterflood on 23-acre spacing would generate $2.9 million cumulative revenue over six years of operation, compared to $1.4 million cumulative revenue over 30 years of operation for a five-spot vertical waterflood. Present values (PV10) for horizontal and vertical five-spot waterfloods in the Wolco Field are $2.3 and $0.4 million, respectively. Horizontal waterflooding responds more quickly to water injection, resulting in significant amounts of incremental oil produced early in the project. This early horizontal waterflood response yields more attractive investment opportunities com-

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pared to vertical waterflood projects.

Initial conditions prior to producing from or injecting into the horizontal wells were determined by taking fluid levels with an acoustic fluid level device in both the idle wells and the new wells. The pressure in the pilot area averages 126 psi. A water supply well (Wolco WS No. 1) was completed with a submersible pump capable of moving 2,000 barrels of water a day from the Arbuckle Formation, which is approximately 500 feet below the Bartlesville. The injection water is transferred directly into the injection well by the submersible pump.

Pumping units have been installed on the two producing wells. The tank battery is capable of handling the produced fluids and disposing of produced water in the Wolco No. 1A disposal well on the north end of the pilot area. The producing wells were completed with insert pumps in the $2\frac{7}{8}$-inch tubing set in the $5\frac{1}{2}$-inch casing in the vertical section of the well. This places the pump inlet 90 feet above the horizontal section of the well. The producing wells began pumping in January 2004.

The Wolco 4A horizontal injection well was completed with a packer in the $5\frac{1}{2}$-inch casing in the vertical section of the well with $2\frac{7}{8}$-inch internally coated tubing to combat the mildly corrosive nature of the injection water. The submersible pump in the water supply well provides the necessary pressure to move the water to the 4A injection well at 0 psi surface pressure. This provides an initial injectivity substantially greater than the historical injectivity of former injection wells adjacent and to the south of the Wolco pilot area.

The horizontal waterflood was fully operational on Dec. 30, 2003. The water supply well began pumping 2,000 barrels a day, all of which was being injected into the Wolco No. 4A horizontal injector. Through July 2004, the horizontal waterflood had produced 1,150 barrels of oil and 32,730 barrels of water. The water supply well had produced 88,846 barrels of water for injection into the Wolco 4A.

After running gamma ray, density, induction and bore hole televiewer logs in both producing wells, it was determined that both the Wolco 5A and 6A wells were drilled too deep into the Bartlesville. Both producing wells had been drilled 20 feet from the top of the Bartlesville, and logs of the lateral sections showed insufficient oil saturations (less than 42 percent) that deep in the reservoir. Grand Resources plugged back the Wolco 6A with cement and redrilled the lateral to stay in the top nine feet of the reservoir, where logs show oil saturations in the 55 percent range. In late August, the redrilled Wolco 6A was being put back into production, and simulation results indicated that economical production should be realized from the well. ❒

Editor's Note: The Osage County horizontal waterflooding project was conducted with the support of the U.S. Department of Energy under Award No. DE-FG26-02NT15452, and endorsed by Principal Chief Jim Gray and the Osage Tribal Council. This article was adapted from SPE 89373, a paper originally prepared for presentation at the SPE/DOE Fourteenth Symposium on Improved Oil Recovery, held April 17-21 in Tulsa.

SpecialReport: Horizontal & Directional Drilling **UPDATE!**

Grand Resources has re-drilled both of the original producing wells in the DOE sponsored pilot area. The reason for re-drilling the horizontal section of the wellbores was to place the laterals higher in the reservoir to encounter more robust oil saturations, and ultimately more economic oil production.

While conducting the re-drill operations on Wolco 6A, mechanical problems required three attempts to produce an acceptable wellbore, hence the well number 6A-4. Wolco 6A-4 was drilled at a 40 degree azimuth heading, see Figure 1, approximately 180 degrees from the heading of the original 6A lateral wellbore. Figure 2 presents the abandoned 6A and the new 6A-4 lateral wellbores as a dashed gray line and a green line respectively. The 6A-4 lateral was drilled 10' higher in the reservoir. Logs run in the horizontal section of 6A-4 show higher oil saturations than the original 6A wellbore. Figure 3 illustrates the difference in position of each 6A lateral relative to the top of the Bartlesville pay.

Results of re-drilling 6A-4:

	BOPD	BWPD
Production prior to re-drilling	2	340
Production after re-drilling	15	135

The second producing well, Wolco 5A, was plugged back and re-drilled as 5A-2. Wolco 5A-2 was also drilled 10' higher in the reservoir and logs are being run as this update was being written. Production results for Wolco 5A-2 are not yet available

Figure 1

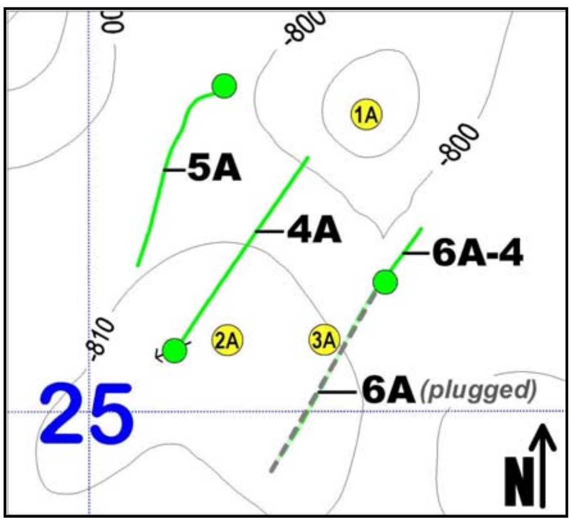


Figure 2

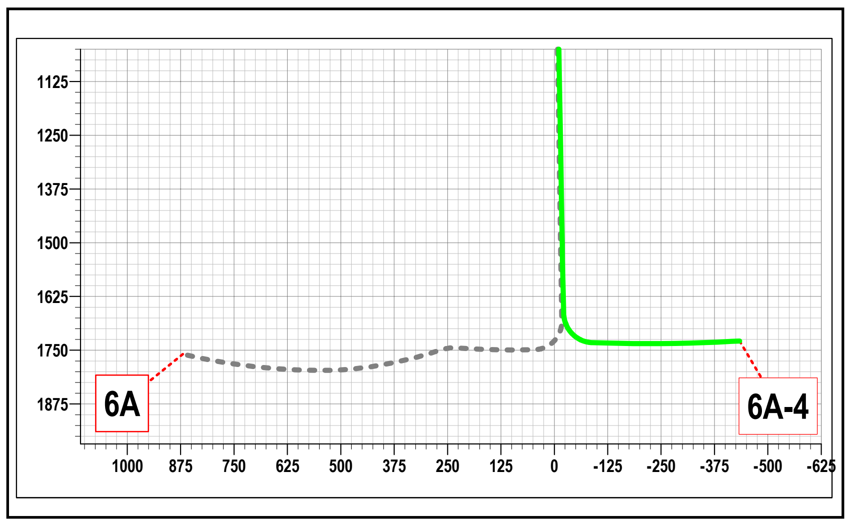
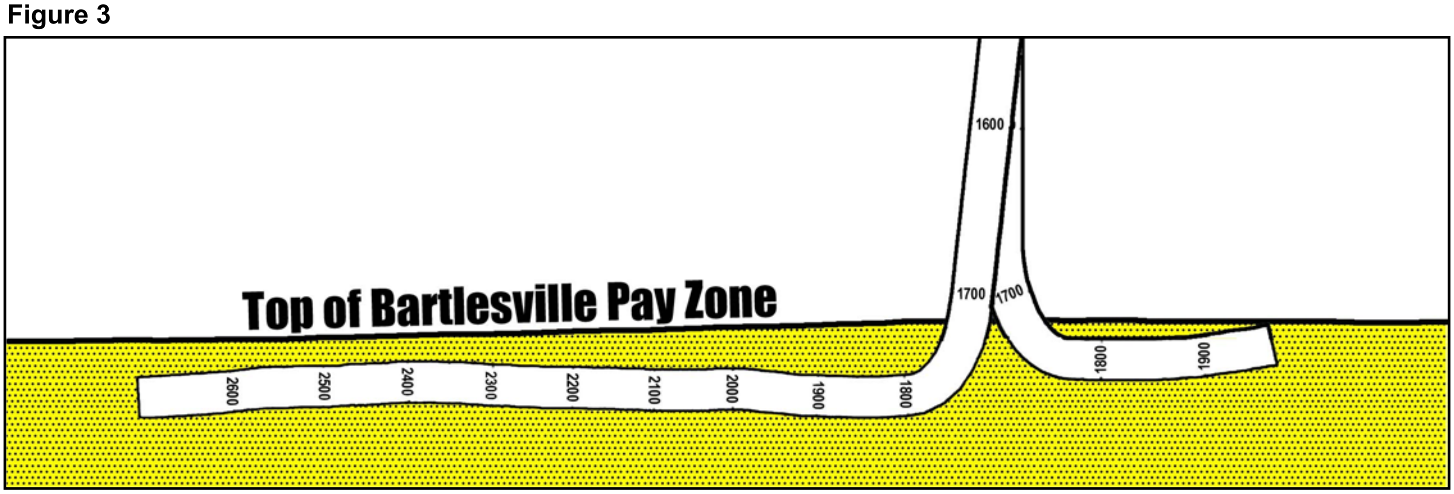


Figure 3



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