SPE 37354

A Case Study for Drilling and Completing a Horizontal Well in the Clinton Sandstone

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This paper was prepared for presentation at the 1996 SPE Eastern Regional Meeting held in Columbus, Ohio, 23-25 October 1996.

Abstract

Horizontal well drilling for the recovery of natural gas and oil has been touted as the panacea for optimum recovery from hydrocarbon reservoirs. This technology has been applied to reservoirs throughout the world, primarily in environments such as the North Sea off the coast of Great Britain and the Austinchalk in Southeastern Texas. To date, very few wells have been attempted in the Appalachian Basin. To test this technology in the Appalachian Basin, a joint effort between Belden & Blake Corporation and the U.S. DOE resulted in the first horizontal well successfully drilled and stimulated in the Silurian Clinton Sand formation. The Central Waste #14 well (CW #14), is located in Smith Township, Mahoning County, Ohio, which is one of the better remaining areas for Clinton Sand developmental drilling. The CW #14 was spudded in October 1993 and drilled to a total measured depth of 6,505 feet at a maximum inclination of nearly 92 degrees from vertical with approximately 1,320 feet of Clinton interval exposed. Total Clinton interval footage greater than 85 degrees was about 1,142 feet. Three hydraulic fracturing stages were successfully completed within the horizontal wellbore. Since this was the first horizontal well drilled in the Clinton Sand interval, considerable knowledge and experience was gained in drilling and completing this well. The actual drilling operation required about 45 days of rig time. The well was stimulated during the summer/fall of 1994 and placed on production in early 1995.

The CW #14 was equipped with a pumping unit and downhole pump and has produced approximately 20,000 MCF of natural gas and 7,000 barrels of oil in its first full year of production. Unlike similar wells drilled in this area, the oil production is about twice that expected while the gas production is less than half of the neighboring offsets. Based on the production performance to date which has displayed a much shallower gas decline rate than a vertical well in the area, the CW #14 is currently estimated to have an ultimate recovery in the range of 330 to 400 MMCFE which is approximately 1.6 to 2.0 times its vertical offset wells.

While we are encouraged with the 1.6 to 2.0 increase in estimated ultimate recovery, horizontal drilling does not appear to be a viable economic alternative for primary development in this area without further improvements in reserve potential along with significant cost reductions. At this time, drilling this type well may be limited to special applications for secondary or enhanced oil recovery or perhaps for natural gas storage. The CW #14 horizontal drillng project, however, successfully demonstrated that the extremely hard and abrasive Clinton Sand can be horizontally drilled and stimulated which we considered a major technical accomplishment for drilling a well of this type in the Appalachian Basin.

Introduction

The Clinton Sand is a low permeable gas reservoir in Northeastern Ohio with initial well production generally in the 75 to 150 MCF per day and 5 to 10 barrels of oil per day. Ultimate production from a vertical well in the Clinton formation in Smith Township, Mahoning County is projected to be about 205 million cubic feet of gas

equivalent based on production from the surrounding wells. Future drilling to the Clinton Sand reservoir may be restricted since many of the potential locations will require some form of directional drilling. Most of the easy, accessible surface locations have already been developed, therefore, leaving those areas that are adjacent to towns or under lakes or streams, or in the case of the Central Waste area, located beneath a surface landfill area. The ability to penetrate this resource along with improving ultimate gas recovery requires the development and successful application of practices such as horizontal drilling.

This report represents a detailed account of events of all field work and supporting activities associated with drilling, completing, testing and stimulating the Belden & Blake/DOE horizontal Clinton Sand well, CW #14. The report is intended to provide information along with dialog as to report on those activities and tasks that worked well and those that did not. The intent of the report is also to point out those areas which will need improvement if horizontal drilling is to be applied on a more regular basis to low permeable tight sandstones as represented by this Appalachian reservoir, recognizing that this is the first horizontal drilling test ever completed in the Clinton Sand in Ohio.

Site Selection

The primary criteria for site selection for this horizontal drilling project was reserve quality and consistency. The Smith Township, Mahoning County area of Ohio was one of the best remaining areas for Clinton Sand development that Belden & Blake had in its acreage inventory. As **Figure 1** represents, the identified project area indicates Clinton reserves in excess of 200 MMCFE which is considered very good for the Clinton formation. In addition to quality and consistent reserves, pay thickness in the project area was approximately 70 feet thick as shown in **Figure 2**. This Clinton pay interval would provide a sizable target versus other Clinton areas with pay zone thicknesses in the 5 to 10 foot range making it more difficult to drill in the horizontal direction.

The anticipated Clinton Sand interval, which is comprised of three members: the Stray, Red, and White, is illustrated in **Figure 3**. . Since the Red Member is believed to have the highest gas saturation, the planned lateral was to be contained in the Red. The path of the wellbore was planned to be drilled on an magnetic azimuth of 156 degrees. A variance was obtained by Belden & Blake with an offset producer west of the drilling unit to allow a lesser distance from their lease boundary normally required by Ohio State law.

Background Information

An integrated drilling plan was developed from several separate but interrelated sources of information including a GRI sponsored vertical test well (CW #12 - GRI Topical Report - CER Corporation Contract No. 5091-212-2242). This information included: openhole stress testing, oriented coring, and geophysical monitoring of the target formation and the surrounding strata with small injection tests (mini fracs) to determine the elastic rock properties through real-time borehole deformation measurements of the Clinton and surrounding strata. These were used in conjunction with an array of tilt meters to determine the orientation of the principal stresses. This information was incorporated with thin-section geologic interpretations to project the most advantageous drill path orientation. The objective was to determine the potentially largest opportunity for intersecting the target interval in a location and at an orientation which provided the greatest exploitation advantage.

A nearby high angle well (CW #7) drilled by Belden & Blake in 1989 was prematurely terminated because of hole problems. The limited in-target footage was not effectively stimulated and had disappointing production. It was drilled with polymer mud and attained a terminal angle of 70.5 degrees and penetrated only 200 feet of the Clinton interval prior to serious hole deterioration problems. Because of this experience, it was decided to employ an intermediate casing string in future wells to eliminate potential hole problems above the Clinton and thereby allow maximum focus on drilling the target formation.

In an effort to improve on this prior experience and to incorporate additional geophysical analytical techniques, a drilling plan was developed which incorporated this prior experience in addition to the information derived from the geophysical testing and analysis.

Drilling Plan Summary

The development of a well plan included decisions relative to build rates, intermediate casing, hole cleaning, hydraulic pressure and volume requirements for both mud and air in the angle building and horizontal hole segments, measurement while drilling (MWD) survey capabilities for tools both in air and in mud mediums, and for downhole motor availability and power outputs with both air and mud.

The plan incorporated a number of these decisions and also resulted in the selection of the primary and secondary service companies. The selection criteria requirements eliminated some service companies because of equipment and organizational limitations and unfamiliarity with the application of their equipment in air drilled environments. One major service company related an unwillingness to participate in air drilling projects.

The design included drilling the target interval with air as a circulating medium to minimize formation damage. The drilling procedure was to include a combination of downhole motors and rotary bottom hole assemblies within the target interval.

The design also included an 8-5/8 inch intermediate casing string installed in the Stray Clinton. The purpose of the intermediate casing was to eliminate the uphole formation

problems encountered while drilling the high-angle CW #7 offset well. The design inclination angle at the intermediate casing point was 70 degrees. The angle building hole segment between the kick off depth and the intermediate casing point was drilled with mud as a circulating medium. This decision was predicated on:

a. Higher degree of survey confidence resulting from the increased quantity of information provided by a mud pulse MWD, resulting in a smoother continuous path to minimize drag.

b. The additional cost of the air volume required to clean the larger diameter hole.

A prognosis was developed to describe and define the drilling parameters and options for drilling horizontally in the Clinton Sandstone. The objective being to drill 1,977 feet horizontally within the Clinton geologic package, which includes the Red and subjacent White Clinton formations. The local dip is 89.8 degrees and the prognosis was developed to obtain tangency in the Red Clinton 34 feet above its base and to maintain an azimuth of 156.5 degrees.

The final selection resulted in the choice of a primary service company which offered an integrated organization which could provide the engineering design and support, downhole motors, and MWD hardware for both air and mud drilling.

The service company support and recommendations became an integral component of the well design and incorporated, at that time, what were believed to be moderate but not maximum build rates (8.81 & 7.88 degrees/100 feet), and MWD hardware suitable for both mud and air drilling scenarios. The following is a more specific summary of the drilling plan:

1) Drive 60 feet of 16 inch conductor pipe.
2) Drill 14-3/4 inch hole to 730 feet (through Berea Sandstone) and set and cement 710 feet of 11-3/4 inch surface casing.
3) Drill 11 inch hole to kickoff depth of 4,373 feet taking single shots every 500 feet.
4) Run continuous directional log to confirm bottomhole position.
5) Kickoff and drill 11 inch hole on brine with 8 inch motor. Build angle at 8.8 degrees per 100 feet at magnetic azimuth 156.5 degrees to top of Stray Clinton (MD-5170 TVD-4985) with a final inclination of 70 degrees.
6) Set approximately 5,170 feet of 8-5/8 inch intermediate casing (24 lb/foot J-55 from 0 to 2,000 feet and 32 lb/foot J-55 from 2,000 to 5,170 feet). Cement with 255 sacks Class A with estimated cement top to 4,100 feet.
7) Blow hole dry and drill maximum of 30 feet to dust hole.
8) Drill 7-7/8 inch hole with 6-1/2 inch air motor at a build rate of 7.88 degrees per 100 feet maintaining 156.5 degree magnetic azimuth. Build to a terminal angle of 89.8 degrees approximately 34 vertical feet into the Red Clinton formation (Red Clinton approximately 66 feet thick).
9) Attempt to hold 89.8 degrees and drill approximately 1,900 feet staying in the Red Clinton interval.
10) Run 4-1/2 inch 11.6 lb/foot M-75 casing to TD with turbulator centralizers spaced to achieve 70 percent standoff. Cement with approximately 560 sacks of 50/50 Pozmix with 10 percent salt and .6 percent Halad 344 to provide estimated cement top to 4,900 feet.

Drilling Operations

Drilling Rig and Support Equipment.

Drilling Rig. A Wilson Mogul 42 trailer rig with two (2) Caterpillar D343 diesel engines with a Wilson 102-300 mast was selected for the project. There was initial concern over maximum hook load requirements if hole problems and the associated drag were encountered. This proved to be a worthwhile concern because the full rated load was required to remove the drill string as the hole was approaching its final TD. Actually, hole degradation was one of the primary reasons that the drilling was discontinued. The hole degradation is probably directly related to the water and soap added at the insistence of the service company in the three (3) unsuccessful attempts to start their air motors. If this liquid had not been added, it is likely that the hole degradation and excessive drag would have been less severe enabling additional footage in the lateral to be obtained. Without the ability to pull 300,000 pounds (8 lines), the hole may have been lost with an expensive drill string in it. The crown sheave was 102 feet above ground level and the racking board was positioned 47 feet above the drill floor. The drill floor was fitted with a Gardner Denver RT 17-1/2 inch rotary table with a 150 ton load capacity, at 100 RPM.

The substructure rating and set back capacity were unspecified by the drilling contractor and were adequate for the drilling operations as bid. There was a design problem that was unanticipated and did cause some additional cost, primarily in additional welding time. The substructure height was shorter than is generally encountered. It was 8.5 feet from ground level to the kelly bushing and the clearance between the top of the intermediate casing and the rotary table was minimal. Fortunately, the conductor and surface casings were set close to ground level. This situation is mentioned because it could have created a significant problem and future planning for wells with intermediate casing strings should require a minimum ground level to kelly bushing height of 10 feet.

Drill Pipe. The drill pipe was 4-1/2 inch internally plastic coated 16.60 lb/foot Grade G and 60 joints of Hevi Wate (trademark) drill pipe were used in the lower portion of the build segment and in the first portion of the lateral segments while approaching the final TD. No drill pipe failures or limitations were experienced.

Mud Pumps. The rig was furnished with two (2) mud pumps, each capable of providing sufficient flow rates to permit powering the downhole motors and cleaning the hole without assistance. This requirement proved to be important because the drilling was continued during periods when the primary pump as its prime mover were being repaired. The primary pump was an EMSCO F1000 (10 inch stroke) with 6.5 inch liners (wp = 1558 psi) powered by a Caterpillar D398T diesel rated at 825 continuous horsepower at 1200 RPM. It was later determined that the engine was capable of approximately 775 horsepower because of a limitation in the diesel injector rack. The pump was typically operated at 495 gallons per minute at a stand pipe pressure of 2200 psi. The standby pump was a Gardner Denver FXN (14 inch stroke) with 5.5 inch liners (wp = 1800 psi) powered by a 12V71 Detroit Diesel rated at 350 continuous horsepower at 1800 RPM. It was capable of delivering a reduced flow, 370 gallons per minute at 700 psi.

Air Compressors / Air Measurement. The air compressors were specifically selected to provide excess air capacity because of the dependence on having a sufficient air volume to power the positive displacement downhole motors, which are known for their inefficiencies, to clean the hole, and the derating required for air packages supplied by drilling contractors. These units were rented at a premium cost from an air rental company. Three (3) screw type compressors were rented. Each was rated at 1200 CFM of oil free air at 290 psi. Each of the three (3) screw compressors and the reciprocating booster compressor was powered by a 8V71 Detroit Diesel rated at 233 continuous horsepower at 1800 RPM. These were installed upstream of a reciprocating booster compressor, Joy WB-12 (6-1/2 x 5) capable of being operated in either a single stage, 3300 CFM at 640 psi or a two (2) stage configuration which would deliver 2300 CFM at 1100 psi. Both single and two (2) stage operations were used during various aspects of the drilling operation, and the excess air availability provided the answer to questions regarding the inability to start the three (3) faulty downhole motors. Because of uncertainties regarding the actual quantities of drilling air being delivered and the importance of this information in operating the air powered mud motors, a 2 inch orifice meter run and Halliburton electronic meter with continuous recording capabilities were installed. This information proved important in addressing questions regarding downhole motor problems.

Light Plants. An additional 25 KW electric power plant was installed to provide power for the directional service companies, company trailer, and back-up for the rig, which proved helpful when the rig power plant was being repaired. The efficiency of the drilling operations would have been reduced without the additional electricity generated.

Drilling Summary. Drilling operations were conducted on site between October 18, 1993 and December 9, 1993 for a total of 53 days. The vertical section was drilled on a contract footage rate of $8.50 per foot by a local contractor. Total days from KOP were 45 days compared to 25 days budgeted with approximately 750 feet less hole drilled than planned. A plot of actual days versus planned days can be seen in **Figure 4**. **Figures 5 and 6** illustrate the actual versus original well path in the plan view and vertical view respectively.

Approximately nine (9) additional days were experienced in the build section prior to cementing the intermediate casing. All of these days were a direct result of mechanical problems which ultimately necessitated a plugback. After examining these mechanical problems, it was determined that some were inexcusable in lieu of the considerable preplanning and conservative well plan.

After setting the intermediate casing, an additional seven (7) days were lost when the 6-1/2 inch air motors would not run on bottom. An inline orifice flow meter indicated sufficient air volume was being pumped. The directional company indicated that the drill pipe scale may have been the source of the problem which has not been confirmed to date.

The lateral was planned to be drilled on dry air, however, soap was employed in an effort to start the air motors. Subsequent attempts to dry the hole were unsuccessful, and the remainder of the hole was soaped. The lateral was prematurely TD'd after drilling approximately 1,320 feet of target due to drill pipe sticking which may have resulted from the soap-mist affect on the shale intervals within the Clinton interval.

Detailed Drilling Operations.

Vertical Section (Surface to KOP-4,367 Feet). The vertical section of the hole was spudded on 10/18/93. Conductor pipe (16 inch) was driven to 87 feet. A 14-3/4 inch hole was drilled to 806 feet with 11-3/4 inch surface casing set at 760 feet and cemented to surface with 500 sacks of cement. An 11 inch hole was drilled utilizing dry air to the kickoff depth of 4,367 feet which was reached on 10/24/93. Eleven slick line retrievable single-shot surveys which provided inclination only were run by the drilling contractor. These single shots ranged from a maximum of 3.5 degrees at 647 feet and diminished to less than 1 degree below 1,813 feet. An openhole continuous directional log confirmed the bottomhole position at kickoff to be north 29.6 feet and west 1.9 feet from vertical.

Kickoff to Intermediate Casing Point (ICP) 4,367-5,115 Feet. The drilling of this segment was executed with an 8 inch mud motor powered by brine water. The

directional information was provided by mud pulse measurement-while-drilling (MWD) survey tools located within the drill string. The hole diameter was 11 and later 10-5/8 inches to accommodate 8-5/8 intermediate casing string.

This segment required nine (9) days longer to drill than anticipated. The additional days were the result of mechanical problems with the MWD directional surveying and mud motor components.

The MWD hardware was incapable of reliable operation at the specified 600 gallon per minute (gpm) flow rate required for hole cleaning. The in-hole components failed twice, causing breakage of a cobalt steel flow restrictor located in the drill string at the top of the MWD tool. Pieces of the flow restrictor passed through the motor, causing internal damage.

The directional service company subsequently advised the maximum allowable flow rate for their tool was now reduced to 400 gpm. Drilling was attempted at this reduced flow rate, but hole cleaning problems became evident and a polymer mud replaced the brine as a circulating fluid. Subsequently, the directional orienting sleeve within the drill string rotated and the MWD alignment with the downhole motor drifted and the hole was drilled off the projected course to an unrecoverable position. The measure point for the tool was 56 feet behind the bit and when the incorrect drift was observed, it was impossible to recover. The hole was then plugged back from 4,965 to 4,550 feet with cement.

This section was redrilled with another style of MWD, which permitted the larger flow rate necessary for hole cleaning. The drilling progressed but the build rate was marginal and, despite several attempts by the service company to adjust motor offset angles and stabilizer diameters. The assembly would not build at their projected build rates. The final result was that the ICP was forced to be set at an inclination angle of 61 degrees rather than the planned 70 degrees.

Intermediate Casing Point to TD 5,115-6,505 Feet. After cementing the 8-5/8 inch intermediate casing, a slick assembly with a 7-7/8 inch tricone bit was run to blow the casing dry with air and drill the float shoe and one (1) foot of formation to dust the hole.

A 6-1/2 inch air motor with an AKO setting of 1.65 was run with Cartridge Data Transmission steering system. However, the motor would not run, and the next seven (7) days were consumed attempting to get a motor to run. Over this span, only 30 feet of hole was drilled placing the hole at 5,154 feet and 65.7 degrees.

Regrettably, the directional contractor was released after a mutually agreed air volume test was performed which the contractor acknowledged should have been a sufficient rate to run the motor. Another directional contractor already on standby, immediately was mobilized to perform the directional drilling services.

Only 289 feet was cut in 9 days from 5,154 to 5,443 feet MD using 6-1/4 inch motors. A wireline steering tool with side entry sub was utilized for directional control. Motors, steering tools, and bits all contributed to length of time to drill this interval. Two steering tools failed in the first 38 feet and the first bit (Hughes ATJ44AD) after 54 feet. Subsequent trips were made to check motor alignment and to increase AKO setting from 1.6 to 2.0, pull a weak Security motor, trip for bit with 46 feet drilled, change motor, and replace a 3 axial probe steering tool with a 2 axial probe. This section of the hole was extremely rough on the motors, bits, and steering tools mainly due to the nature of the hard, abrasive Clinton Sandstone. Five BHA's were utilized in this 289 foot interval where penetration rates averaged only 32 feet of hole drilled per day. Inclinations ranged from 66.2 degrees at 5,154 feet to 87.7 degrees at 5,443 feet which provided an
average build rate of 7.4 degrees per 100 feet. Obviously, major improvements must be made if the Clinton Sand is to be air drilled with downhole motors and conventional steering tools.

Due to the lack of success with the motors and budget restrictions, it was decided to drill the remainder of the well with rotary assemblies attempting to slightly build in an effort to keep the drill path within the Clinton interval, even though it may be in the shale between the Red and White members. It was believed that a hydraulic frac would penetrate the Red and/or White even if it initiated in the shale between the two.

Therefore, drilling resumed with rotary BHA's from 5,443 to 6,505 feet (TD). The rotary BHA #1 which included bit, 3 point near bit roller reamer with chert cutters (6.62 feet) float sub, survey collar (31.19 feet), and compressive service nonmagnetic drill pipe (31.28 feet). This assembly, drilled from 5,443 to 5,860 feet (417 feet), indicated the angle built from 87.8 to 91.7 degrees in the first 100 feet then dropped at 0.8 degrees per 100 feet. Inclination at 5,860 feet was 85.7 degrees.

Rotary BHA #2 which was identical to BHA #1 drilled from 5,860 to 6,105 feet. Inclination built from 85.7 to 86.9 degrees in the first 190 feet then dropped at 0.7 degrees per 100 feet to a final inclination of 86.3 degrees at 6,105 feet.

Rotary BHA #3 drilled from 6,105 to 6,169 feet when the decision was made to pull this BHA and to go back in the hole with an IBS (Integral Blade Stabilizer). The inclination built from 86.3 degrees at 6,105 feet to 87.4 degrees at 6,169 feet.

Rotary BHA #4 including an IBS was used to drill from 6,169 to 6,313 feet. At 6,289 feet, the angle had built from 87.4 to 89.4 degrees. This BHA was pulled due to low ROP at 6,313 feet. The bit was 2/16 inch out of gage and the IBS was 1/2 inch out.

Rotary BHA #5 with another IBS was run and drilled to 6,505 feet where drilling was stopped to run a survey.

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