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The New Generation of Rotary Systems May be Closer Than You Think

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Abstract

Validus® International Company, LLC is introducing the industry’s third generation of rotary steerable systems. The first generation of tools used closed loop control systems to drill straight ahead. The second generation will use a closed loop system to control curvature rate. The third generation will autonomously steer the tool to hit the directional or horizontal targets.

Baker Hughes introduced the first generation with their AutoTrak in 1998. Validus® NAS/DS AUTOGUIDE™ may become the industry’s first tool to transcend the second and provide the third.

The NAS/DS controls curvature rate by precisely adjusting the radial extension of the stabilizer blades on a near bit Non-Rotating Stabilizer. The closed loop control process corrects for the secondary effects caused by formation characteristics, bit and tool wear, and manufacturing tolerances. The downhole trajectory control is provided by the Directional Solution™ software package. This novel tool calculates the optimum 3-D circular arc paths needed to hit the directional and/or horizontal targets. The combination of these technologies will provide smoother bore holes, reduced drilling time, and incredible targeting precision. The tool is designed to operate with any Measurement While Drilling and /or Logging While Drilling product available in the industry.

Validus® has completed the design and lab testing of this 3rd generation stand-alone rotary steerable system and plans to field test a 6 ¾ in. prototype in 2003. The tool will control curvature rates from 0 to 15°/100 ft. in 8 ½ inch holes with bit weights up to 55,000 lbs.

Introduction

Warren[1] and Purdue[2] have published timelines that show the significant industry milestones in developing directional drilling equipment. Figure 1 is a version of the timeline starting with the first positive displacement mud motor and ending with the significant goals expected to be achieved later this year. The timelines show that while we have come a long way we note that the advances were preceded by a well established need defined by the operators. Steering tools, MWD’s and steerable motors were all demanded by industry well before their introduction. The same is apparent in the evolution of the rotary steerable systems. The 2-D. systems were barely introduced before everyone wanted 3-D. tools. Then, when the first closed loop drill straight ahead systems were introduced we heard the calls for tools that would handle a larger share of the directional drilling operations and eventually to drill autonomously.[3] The industry is already drilling conventional steerable motor sections with the straight-ahead rotary steerable tools. But, if we follow the normal evolutionary process we should not be too far away from a new generation of rotary steerable tools that are designed to control curvature rate most likely in a closed loop control process. Then in a few more years, we should expect to see equipment that will automatically drill to the directional or horizontal targets.

We expect to set the next two milestones in rotary steerable system development later this year. The NAS/DS system utilizes two revolutionary technologies. The downhole directional tool uses a patented Non-rotating Adjustable Stabilizer (NAS) design that provides precise control of curvature rate. The directional drilling operations are automatically controlled by a downhole computer code called the Directional Solution (DS). (Patent pending). This tool computes the positions of the borehole after each survey and determines the optimum three dimensional circular arc trajectories required to hit the directional and horizontal targets.

Validus Rotary Steerable System

We have completed the design and lab testing of an autonomous standalone rotary steerable system and will field test a 6 ¾ in. prototype later this year. It will produce zero to 15°/100 foot curvature rates in 8½ inch holes with bit weights up to 55,000 lb. The bottom hole assembly consists of a Non-Rotating Adjustable Stabilizer, a fixed stabilizer, a flex joint and a Communications Link (CL). See Figure 2. The Validus system records near bit directional surveys and transmits them to the surface through the communications link. The surface system can send changes in the target specifications or directional parameters to the NAS through the communications link. The NAS system can be run with all service company’s

MWD or LWD systems.

Only a single BHA is needed to drill from the kickoff point or even above that depth to the total depth of a directional or horizontal well. This eliminates all of the trips required to modify the directional performance of conventional assemblies. The NAS can be run with the optimum bit, use the most effective weight and rotary speed and apply all of the available hydraulic energy to the bit.

Directional Drilling Control System

The critical feature for directional drilling with a rotary steerable system is the ability to control curvature rate. The NAS controls curvature rate by precisely positioning the five individual blades on the near bit adjustable stabilizer.

The control system positions the adjustable blades to give full-gauge contact on the loaded side of the hole while providing free sliding clearances for the blades located on the non-loaded side of the hole. Utilizing five adjustable blades provides stable support regardless of the orientation of the stabilizer. The NAS utilizes a jackscrew in an inclined ramp to position each individual blade. By tracking the revolutions of each drive motor the radial positions of each blade can be controlled to within 0.0001in.

The NAS design allows the utilization of the well established three-point geometry solution to obtain the desired curvature rates. As is shown in Figure 3 the wellbore curvature is defined by the contact between the gauge surface of bit and the hole and the contact points between the hole and the two stabilizers located immediately above the bit. The misalignment of these three contact points describes a circular arc that closely matches the curvature performance of a directional drilling assembly.

The downhole software provides closed loop control of curvature rate. It uses the difference between the planned and the actual trajectories on the most recent surveys to compute adjustment factors that will correct for the observed differences. The software uses a weighted running average process in order to rapidly respond to changes in the hole conditions while avoiding the effects of the random survey errors. The goal of this process is to correct for the secondary effects on curvature rate caused by manufacturing tolerances, bit and tool wear, and formation effects.

Autonomous Trajectory Calculations

Circular arc trajectory equations have been available for many years.[4] These equations provide a direct solution for calculating coordinates of a survey, but cannot be reversed to calculate the trajectory needed to hit a target. Fortunately, we discovered a direct method to calculate the required trajectory of a three-dimensional circular arc from the coordinates of the target. This solution provides the basis for a directional horizontal planning program that is installed in the NAS.

The optimum directional trajectory consists of a combination of circular arcs and straight line segments. All directional targets can be intersected with a trajectory that includes either one or two circular arc segments. In most cases, the required trajectory is a single circular arc that may be followed by a straight tangent interval. See Figure 4. In the remaining cases the required trajectory consists of two circular arc segments that may be separated by a straight tangent section. See Figure 5.

For horizontal targets the required trajectory is also limited to either one or two circular arc segments. For the initial landing we typically need only a single circular arc. See Figure 6. For all other cases, the trajectory requires two circular arcs. See Figure 7.

The trajectory program requires minimal input. The user specifies the optimum and maximum curvature rates versus depth for directional targets and the optimum and maximum for horizontal targets. For directional targets we must specify the target coordinates, the target radius, and the operator's preference between adjacent targets. We also have the option of specifying the required target entry angle and azimuth. For horizontal targets we specify the coordinates of a point in the target plane, the dip angle and azimuth of the target plane and the azimuth of the horizontal section.

The simplicity of the new circular arc solution allows us to search for the optimum design. For directional wells the search process parallels the following steps:

1. The program attempts to hit up to the first three directional targets with a single circular arc trajectory and a straight tangent section, if necessary, while using the optimum curvature rates.
2. If it fails to hit any of the targets, the next step is to increase the curvature rate and repeat step one. Curvature rates are increased until the targets are either intersected or we reach the maximum allowable rates.
3. If we can't intersect all of the targets, we determine if a two circular arc trajectory will succeed. The optimum two-circular arc trajectory is found by gradually raising the kickoff point of the deeper targets. The process is continued until we intersect all the targets or find that continuing to raise the kickoff point becomes ineffective.

4. If we have been unable to intersect all of the targets we optimize a missing strategy. We use the operator's targeting preference for this step. The operator specifies if adjacent targets are of equal value or whether the upper or lower target is more valuable. If missing the less valuable target helps, we determine if we can intersect the more valuable target by missing the less valuable target by less than the specified target radius. Next we allow the preferred target to be missed by up to the specified target radius, and lastly we allow the less valuable target to land beyond the specified target radius.
5. After either identifying a trajectory that hits all of the targets or includes the optimum strategy for missing, we perform one additional optimization step. We use the operator's specified neutral point to calculate the torque required to rotate the drill string. We determine if the torque is reduced by elevating the kickoff points of the deeper targets. We select the trajectory that produces the lowest possible torque.

The design process for horizontal targets is much simpler than for directional targets, because we are only concerned with hitting a single horizontal target specification at a time. The operator specifies the minimum, optimum and maximum curvature rates to be used in the build curve. They also specify the maximum and minimum curvature rates to be used in the dual circular arc trajectories. The design process follows the following steps:

1. Determine if we can land on the target plane using a single circular arc trajectory. If the required curvature rate is between the minimum and maximum specified, this is the solution.
2. If the single circular arc curvature rate is less than the minimum, we add a straight tangent interval above a minimum curvature rate circular arc.
3. If the required single circular arc curvature rate is greater than the maximum rate or if we can't hit the target with a single circular arc we use the two circular arc solutions. The dual circular arcs are designed using the specified optimum curvature rate.
4. If the total dogleg in the dual arc trajectory is less that the optimum curvature rate, the curvature rate is set equal to the dogleg.

The automated process allows us to utilize the smoothest possible trajectory. On conventional operations where the directional driller is required to follow the original targeting plan, each correction requires two doglegs: the first to direct the path back towards the plan and the second to realign the path with the original plan. By calculating the optimum path after each survey we limit the corrections to single and much smaller adjustments. We can also optimize the trajectories used to drill tangent sections or to track horizontal targets. We limit the size of the doglegs in these intervals by setting the curvature rate for these corrections to be numerically equal to the size of the dogleg. This spreads the corrections over 100 ft intervals and significantly reduces the influence of random survey errors.

The process becomes fully transparent to the operator. The directional program shows the operator the optimized trajectory immediately after each survey. It defines the trajectory required to land on the horizontal target or how to intersect the next three directional targets. It also defines the expected targeting precision and the curvature rates that are required. These values indicate the relative ease or difficulty we will have in hitting the targets. If the required curvature rates are at or near the specified optimum rates, we can be virtually assured of hitting the targets. However, if the required rates are close to the maximum rates there is a greater chance of encountering problems.

Directional Drilling Simulator

A directional drilling simulator was developed to help us evaluate the closed loop curvature rate control system of the NAS and the autonomous trajectory planning software. The directional simulator allows us to specify the size of the curvature rate performance errors of the NAS tool and the magnitude of the random errors in the survey measurements. The simulator uses the directional solutions software to calculate the optimum trajectory for drilling the next joint. The simulator creates the following calculation sequence:

1. The simulator uses the directional solution software to calculate the trajectory required to drill the next joint.
2. The simulator uses the latest curvature rate correction factors to define the trajectory settings that will be used by the NAS.
3. The simulator combines the specified curvature rate performance errors of the NAS with the trajectory settings to determine the actual path of the hole.
4. The simulator determines the true inclination angle and azimuth at the next survey depth.
5. The specified standard deviations of the random survey errors and a random number generator are used to calculate the inclination and azimuth error for the next survey.
6. The true angles are combined with the calculated survey errors to determine the actual surveys.
7. The actual surveys are used to calculate the

position of the hole at the latest survey.

8. The desired trajectory is interpolated between the last two survey points and compared with the curvature rate calculated between the surveys.
9. The difference between the desired trajectory and the curvature rate calculated from the surveys is used to update the curvature rate correction factors.

The process is repeated until the well reaches total depth. The simulator defines the targeting error by interpolation for the directional targets and by computing the vertical distance between the surveys and the sloping plane of a horizontal target.

Targeting Performance for a Directional Well

We have simulated the results of drilling a directional well with four targets. Table 1 lists the target and directional drilling specifications needed for the downhole trajectory calculations and the error specifications used by the simulator. In this example, the first three targets approximate fault traps that are not aligned with the path from the surface location. The fourth target is located off the fault trap trend to show how the three target trajectory calculation handles the additional target. The specifications include the drill string dimensions and neutral point depth that are used to minimize the rotating torque. The error specifications in Table 1 define the actual curvature rate performance of the tool and the magnitude of the random survey errors used by the simulator. The tool performance error is defined as a -0.5°/100 ft fixed offset error, a –5% variable build rate error and a +5° toolface alignment error. The random survey errors are defined as a 0.1° standard deviation error in the inclination angles and 0.3° standard deviation error in the azimuth angles. These values are believed to be the maximum credible errors for the NAS tool and for conventional directional surveying instruments.

The downhole trajectory calculations are performed after each survey. Table 2 shows the calculated trajectories at the kickoff point and after penetrating each of the first three targets. At the kickoff point we need a two circular arc trajectory for the first target and single circular arc trajectory for the next two targets. After penetrating the first target, the next three trajectories are single circular arcs. However, after penetrating the second target the trajectory for the third target becomes a two circular arc trajectory. This change was produced by the rotary torque optimization routine. Figures 8, 9, and 10 are three dimensional plots of the trajectories calculated at the kickoff point and after penetrating the first and fourth targets.

The targeting results of this simulation are shown in the upper block of Table 3. All four of the targets were intersected within a foot of the target specifications. Table 3 also includes targeting results for this directional well plan if the tool and survey error specifications are set to zero or if we double the initial error values. In both of these cases the target intersections remained within a foot of the target specifications.

The precision is especially remarkable because the formats of the error correction process are quite different than the format of the error specifications used in the simulator. The closed loop process uses a weighted running average of the differences between the curvatures calculated from the surveys and the planned curvature to produce a correction independent of curvature rate. The error simulator includes an error component that is proportional to curvature rate. The apparent independence of our targeting precision from the size of the error specification shows that our closed loop correction process is especially robust and should be expected to consistently hit directional targets within a few feet.

The last section in Table 3 shows the targeting precision while drilling with stands and only surveying before connections. This increased the maximum error to three feet.

Targeting Performance for Horizontal Targets

We also used the directional simulator to investigate the targeting performance in a horizontal well. Table 4 shows the input data for the horizontal well simulation. We have simulated drilling a horizontal well that included three geologic target changes. The first two changes simulate the target plane adjustments that are identified while drilling the build curve. The final adjustment simulates a target plane shift that would be required after drilling through an upthrown fault.

Figure 11 and the top of Table 5 show the trajectory plans for this well at the kickoff point. The trajectory is a single circular arc with an 11.2°/100 ft build rate. Figure 12 shows the trajectory plan after identifying the first geologic target change. Table 5 shows that the required trajectory is a short tangent section followed by a single circular arc build curve that utilizes the minimum curvature rate. Figures 13 and Table 5 show similar results for the second geologic targeting change.

Figure 14 and Table 5 show the trajectory plan after identifying the upthrown fault in the target plane. Figure 15 and Table 6 show the simulated actual trajectory of the well path. The wellbore reached the target plane within 50 ft of the originally planned landing and stayed within a couple of feet before locking in on the target plane.

Table 6 lists the surveys produced by the simulator for this well. The last column of the table shows the vertical height between each survey and the current geologically defined target plane. This value is a good measure of the performance of our closed loop correction process and our downhole trajectory calculations. In spite of the size of the random survey errors, the process provides an extraordinary level of target tracking. Note that between 9740 ft and 9990 ft the well path stays within 0.15 ft of the target plane.

Conclusions

1. The directional error simulator provides a realistic test of the expected field performance of our closed loop control process and downhole trajectory calculations
2. The NAS/DS system will intersect directional targets within a few feet.
3. The NAS/DS system will provide extraordinary tracking precision for horizontal targets.

References

[1] Warren, Tommy,: "Technology Gains Momentum," *Oil & Gas Journal* (Dec. 21, 1998) 101.

[2] Perdue, Jeanne M.: "Smooth Steering, Substantial Savings," *Hart's E & P* (Oct. 2001) 63.

[3] Hart's E & P Staff Report, "Power Steering Drilling," (Sept. 2002) 20.

[4] "Directional Drilling Survey Calculation Method and Terminology," *API Bulletin D20*, (Dec. 31, 1985).

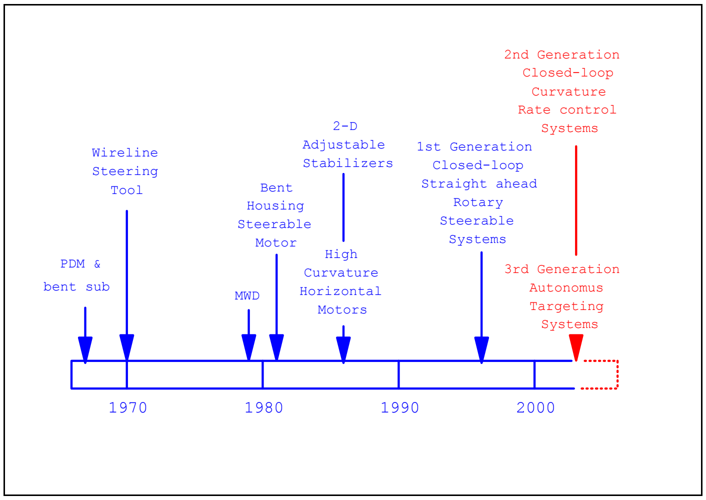

Figure 1. Directional Drilling Technology Timeline

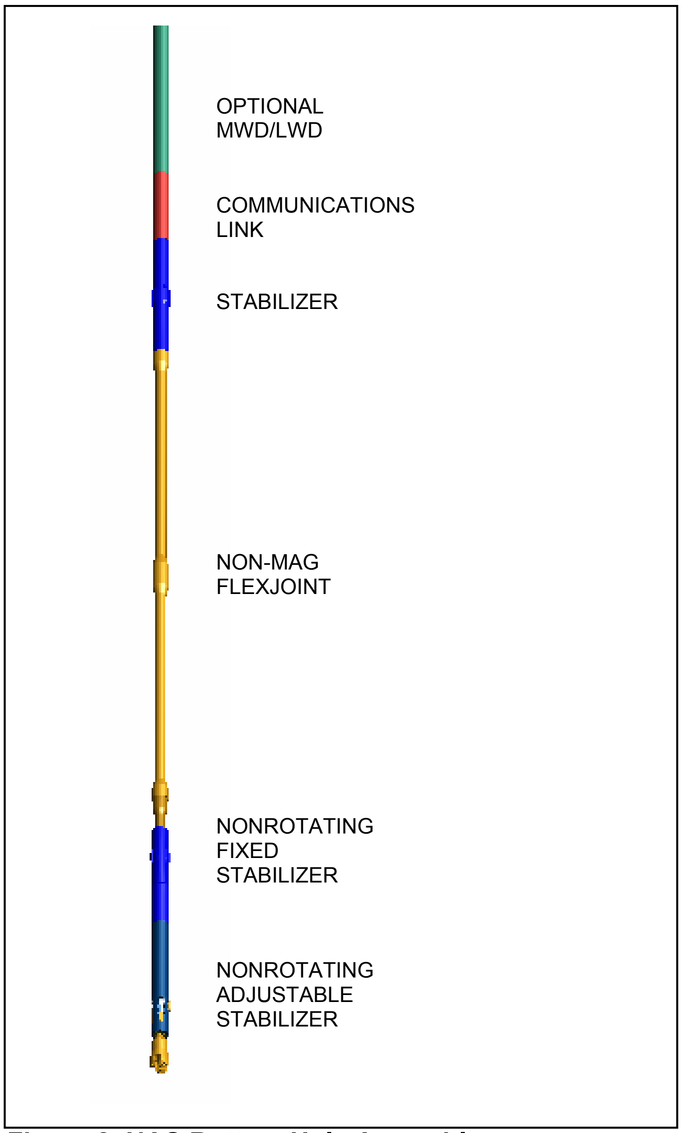

Figure 2. NAS Bottom Hole Assembly

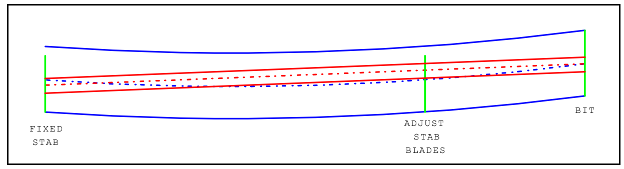

Figure 3. Three-Point Geometry Contact Points

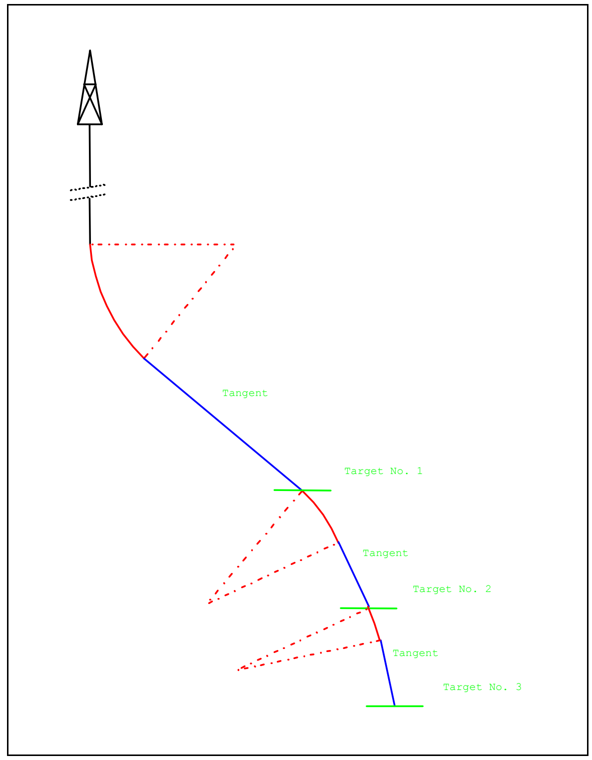

Figure 4. Single Circular Arc Trajectories

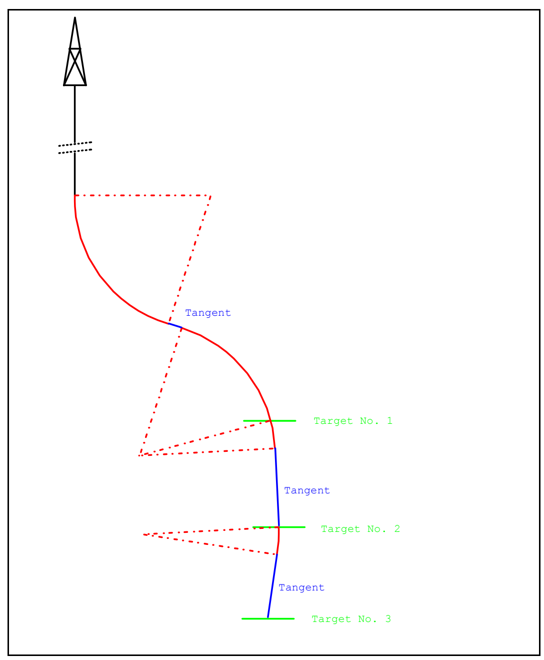

Figure 5. Two Circular Arc Trajectory

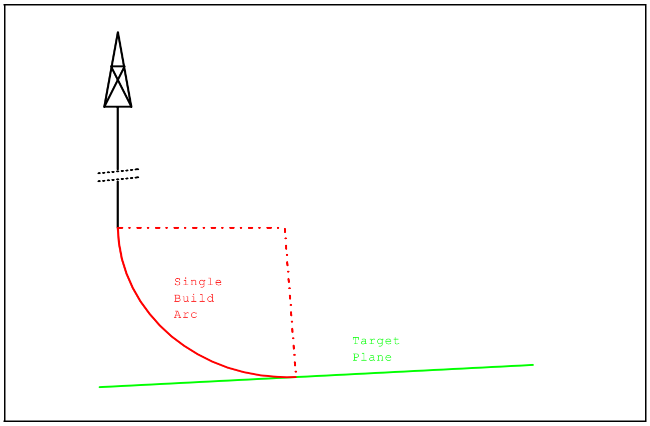

Figure 6. Single Circular Arc for a Horizontal Target

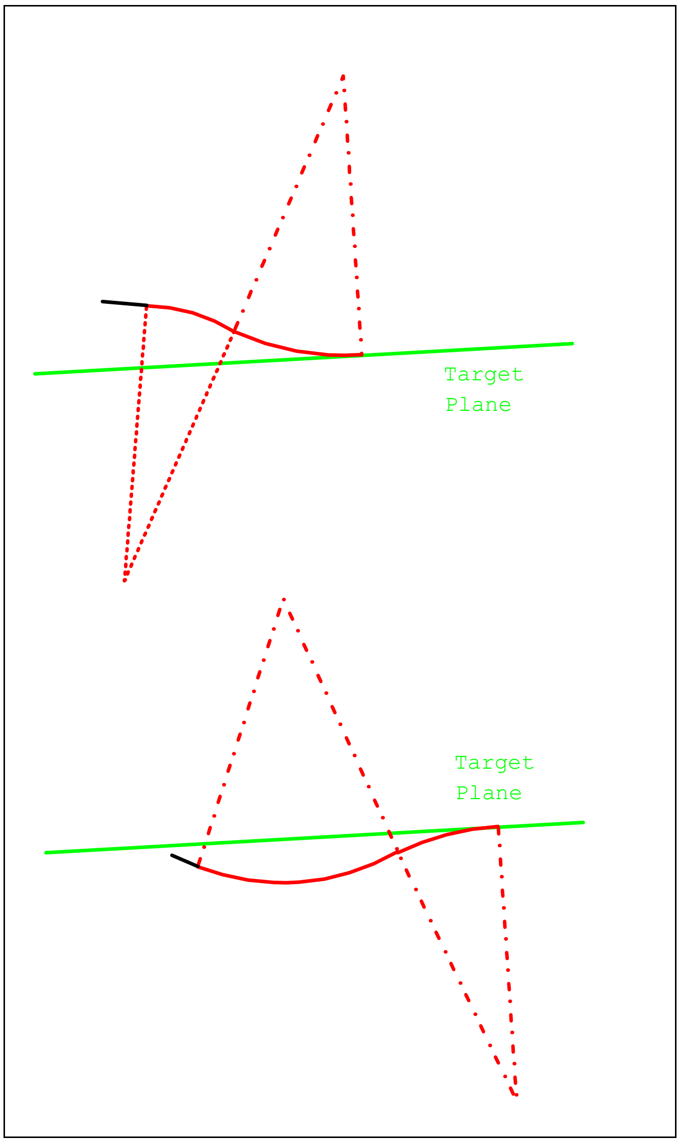

Figure 7. Two Circular Arcs for a Horizontal Target

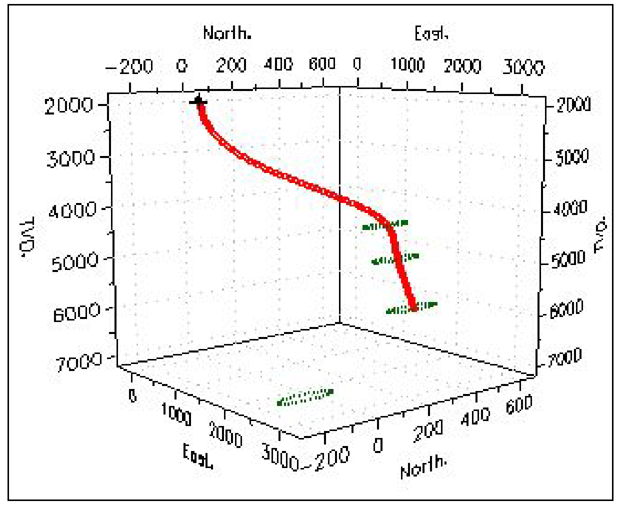

Figure 8. Four Target Directional at the KOP

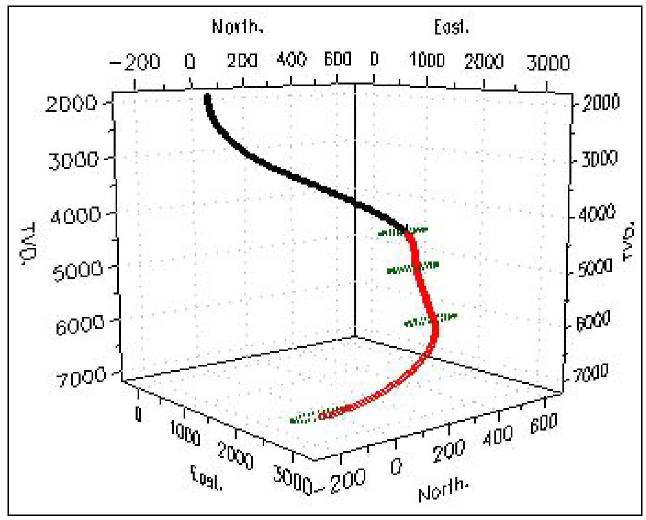

Figure 9. Four Target Directional at First Target

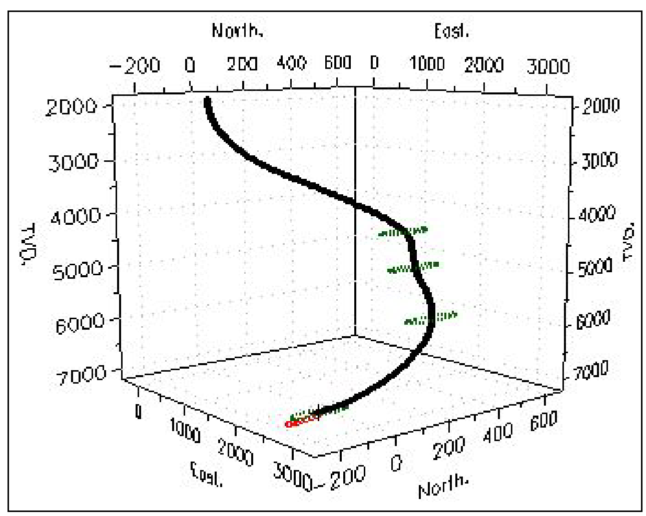

Figure 10. Four Target Directional at Total Depth

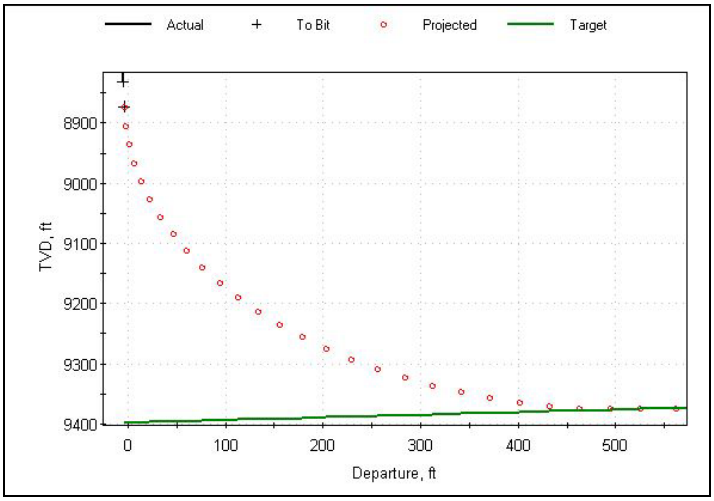

Figure 11. Planned Trajectory at Kick-off Point

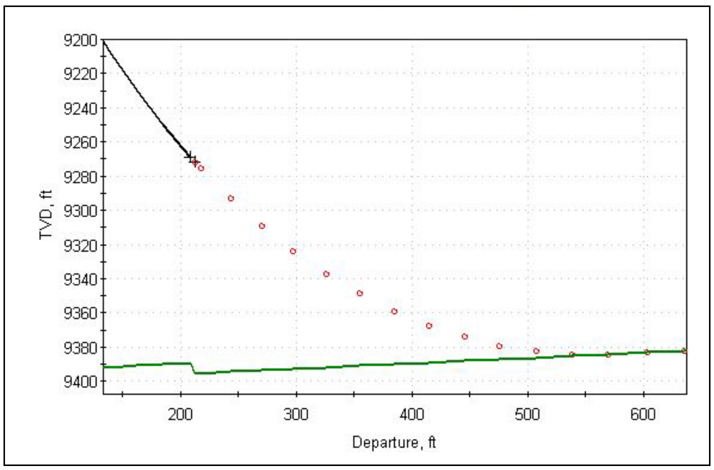

Figure 12. Trajectory Plan Following the First Geologic Targeting Change

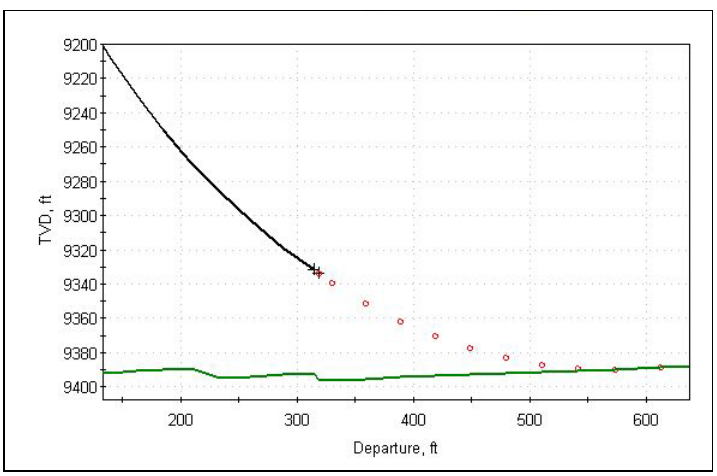

Figure 13. Trajectory Plan After the Second Geologic Targeting Change

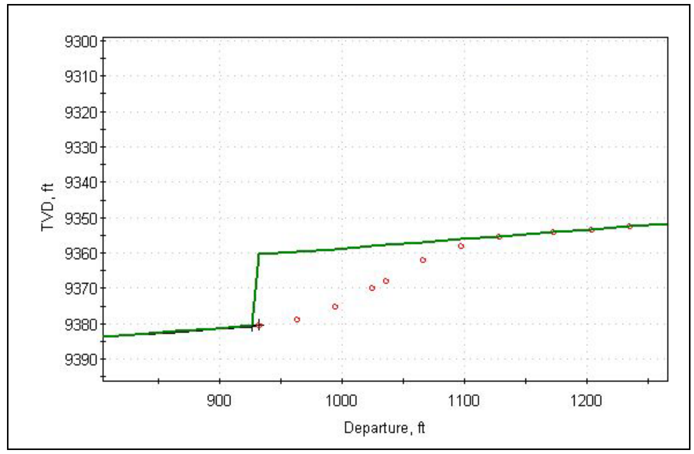

Figure 14. Trajectory Plan After Identifying a Fault

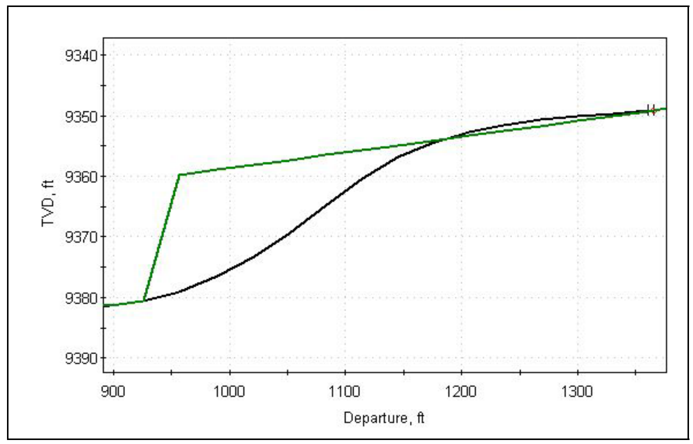

Figure 15. Actual Trajectory Fault Adjustment

Table 1. Input Data for Directional Simulation of a Four Target Directional Well

Target Specifications

Target Number	TVD ft	North ft	East ft	Target Radius	Target Preference	Fixed Entry
1	4,500	500	1,400	100	Same	No
2	5,000	400	2,000	100	Same	No
3	5,700	300	2,700	100	Same	No
4	7,000	-100	2,600	100	Same	No

Final Target Vertical Thickness = 60 ft
Additional Rat Hole = 150 ft

Tie-in Survey

	MD , ft	Angle deg	Azimuth degN	TVD ft	North ft	East ft
1st Survey	1,930	1.5	70	1,930	0	0
2nd[d] Survey	1,960	1.5	70			

Kick-off Point = 2,000 ft
Vertical Section Azimuth = 90.0 dN

Curvature Limits

Pipe OD = 5.000 in
Pipe ID = 4.276 in
Pipe Weight = 22.5 lb/ft
Tool Joint OD = 6.500 in

API Min Yield = 135.0 ksi
Mud Density = 10.00 ppg

Maximum curvature rate of the tool = 15.00 deg/100ft
Maximum Angle = 70.00 deg
Distance of MWD survey sonde to TMD = 5 ft

Design Curvature Limits

From TVD ft	To TVD ft	Design Build Rate deg/100ft	Maximum Build Rate deg/100ft	Design Drop Rate deg/100ft	Maximum Drop Rate deg/100ft
2,000	3,000	2.5	5.5	2.5	5.5
3,000	4,000	3.0	6.0	3.0	6.0
4,000	5,000	3.0	6.0	3.0	6.0
5,000	6,000	3.5	6.5	3.5	6.5
6,000	7,000	3.5	6.5	3.5	6.5
7,000	8,000	4.0	7.0	4.0	7.0

Error Specifications

Constant vertical build rate performance error = -0.50 deg/100ft
…..Variable build rate error (as a percent of the desired build rate) = -5%
Fixed Toolface Error (enter in degrees clockwise) = 5.00 deg
Random inclination angle survey error (standard deviation) = 0.10 deg
Random azimuth angle survey error (standard deviation) = 0.30 deg

Table 2. Calculated Trajectories for the Four Directional Target Example

CALCULATED TRAJECTORY FROM THE KICK-OFF-POINT

Segment Description	Segment Length ft	Measured Depth ft	Inclination Angle deg	Azimuth Angle degN	Dogleg Deg/hft	TVD ft	North ft	East ft	Target Number
bit position	40.0	2000.0	1.5	70.0	0.0	2000.0	0.6	1.7	
Build	1544.2	3544.2	40.1	65.9	2.5	3416.4	218.9	493.4	
tangent	780.9	4325.1	40.1	65.9	0.0	4013.7	424.3	952.6	
Build	668.5	4993.6	47.5	93.0	3.0	4500.0	500.0	1400.0	1
Build	222.7	5216.4	51.1	100.5	3.0	4645.2	479.9	1567.5	
tangent	565.1	5781.5	51.1	100.5	0.0	5000.0	400.0	2000.0	2
Drop	192.2	5973.6	44.7	97.9	3.5	5128.8	377.2	2140.6	
tangent	803.2	6776.8	44.7	97.9	0.0	5700.0	300.0	2700.0	3

CALCULATED TRAJECTORY AFTER DRILLING THE FIRST TARGET

Segment Description	Segment Length ft	Measured Depth ft	Inclination Angle deg	Azimuth Angle degN	Dogleg Deg/hft	..TVD …ft	North …ft	East ..ft	Target Number
bit position	5.0	5004.9	45.8	91.7	4.4	4511.1	500.3	1411.0	
build	326.1	5331.0	52.1	101.6	3.0	4725.5	470.9	1654.5	
tangent	447.0	5778.0	52.1	101.6	0.0	5000.0	400.0	2000.0	2
drop	236.6	6014.6	44.4	97.6	3.5	5157.5	370.2	2173.8	
tangent	759.0	6773.6	44.4	97.6	0.0	5700.0	300.0	2700.0	3
drop	1544.5	8318.1	57.4	249.6	6.3	7000.0	-100.0	2600.0	4

CALCULATED TRAJECTORY AFTER DRILLING THE SECOND TARGET

Segment Description	Segment Length ft	Measured Depth ft	Inclination Angle deg	Azimuth Angle degN	Dogleg Deg/hft	..TVD …ft	North …ft	East ..ft	Target Number
bit position	5.0	5810.7	51.3	99.7	3.5	5020.5	395.6	2025.3	
drop	127.4	5938.1	47.8	96.2	3.5	5103.1	382.1	2121.2	
tangent	420.4	6358.5	47.8	96.2	0.0	5385.7	348.7	2430.8	
drop	417.9	6776.4	34.5	105.6	3.5	5700.0	300.0	2700.0	3
build	1468.0	8244.4	47.0	244.8	5.1	7000.0	-100.0	2600.0	4
TD	237.9	8482.3	47.0	244.8	0.0	7162.4	-174.1	2442.6	

CALCULATED TRAJECTORY AFTER DRILLING THE THIRD TARGET

Segment Description	Segment Length ft	Measured Depth ft	Inclination Angle deg	Azimuth Angle degN	Dogleg Deg/hft	..TVD …ft	North …ft	East ..ft	Target Number
bit position	5.0	6809.7	35.2	105.5	5.4	5727.2	294.9	2719.0	
build	1449.2	8258.9	49.1	246.4	5.4	7000.0	-100.0	2600.0	4
TD	241.7	8500.6	49.1	246.4	0.0	7158.2	-173.1	2432.5	

Table 3. Targeting Precision

MAX EXPECTED TOOL AND SURVEY ERRORS

Target number	Actual MD ft	TVD (ft)	North (ft)	East (ft)	Radius ft	Angle deg	Azimuth degN
1		4,500	500.0	1,400.0	100		
	4,989	4,500	500.6	1,399.7	0.7	45.5	90.7
2		5,000	400.0	2,000.0	100		
	5,778	5,000	400.1	1,999.9	0.1	51.9	100.3
3		5,700	300.0	2,700.0	100		
	6,776	5,700	299.9	2,699.9	0.1	36.7	104.4
4		7,000	-100.0	2,600.0	100		
	8,261	7,000	-99.9	2,600.2	0.2	49.8	244.1

ZERO TOOL AND SURVEY ERRORS

Target number	Actual MD ft	TVD (ft)	North (ft)	East (ft)	Radius ft	Angle deg	Azimuth degN
1		4,500	500.0	1,400.0	100		
	4,981	4,500	500.0	1,400.0	0.0	45.4	90.3
2		5,000	400.0	2,000.0	100		
	5,769	5,000	400.0	1,999.9	0.1	52.2	102.1
3		5,700	300.0	2,700.0	100		
	6,767	5,700	300.0	2,700.0	0.0	36.8	102.9
4		7,000	-100.0	2,600.0	100		
	8,252	7,000	-99.6	2,600.6	0.7	47.5	246.5

DOUBLE MAX EXPECTED TOOL AND SURVEY ERRORS

Target number	Actual MD ft	TVD (ft)	North (ft)	East (ft)	Radius ft	Angle deg	Azimuth degN
1		4,500	500.0	1,400.0	100		
	4,995	4,500	500.2	1,400.3	0.4	46.1	88.4
2		5,000	400.0	2,000.0	100		
	5,785	5,000	399.7	1,999.8	0.4	54.0	104.2
3		5,700	300.0	2,700.0	100		
	6,784	5,700	299.9	2,699.9	0.1	35.8	106.0
4		7,000	-100.0	2,600.0	100		
	8,257	7,000	-99.5	2,600.4	0.6	46.2	245.1

DRILL AND SURVEY IN 94 ft STANDS USING MAX EXPECTED ERRORS

Target number	Actual MD ft	TVD (ft)	North (ft)	East (ft)	Radius ft	Angle deg	Azimuth degN
1		4,500	500.0	1,400.0	100		
	4,996	4,500	500.2	1,399.3	0.7	46.2	88.7
2		5,000	400.0	2,000.0	100		
	5,786	5,000	399.0	1,999.2	1.3	51.8	102.1
3		5,700	300.0	2,700.0	100		
	6,785	5,700	300.4	2,700.0	0.4	34.6	108.2
4		7,000	-100.0	2,600.0	100		
	8,249	7,000	-97.9	2,602.1	3.0	42.2	244.9

Table 4. Input Data for Directional Simulation of a Horizontal Well With 3 Geologic Target Changes

Target Specifications

Geologic Target Sequence	Starting Measured Depth ft.	Dip Angle of Target Plane deg	Azimuth of the Dip degN	Target Plane TVD, ft	Target Plane North ft	Target Plane East ft	Horizontal Target Azimuth dN.	Total Measured Depth ft
1	8,775	2.5	135	9,398	0	0	320	10,600
2	9,265	1.8	135	9,395	175	-146	320	10,600
3	9,385	1.5	135	9,396	254	-213	320	10,600
4	10,000	1.5	135	9,360	726	-609	320	10,600

Tie-in Survey

	MD ft	Inclination Angle deg	Azimuth degN	TVD ft	North ft	East ft
1st Survey	8,700	1.5	296	8,798	10	21
2nd Survey	8,733	1.4	295			

Directional Specifications

Maximum allowable curvature in the build curve = 13.00 deg/100ft
Minimum allowable curvature in the build curve = 10.00 deg/100ft Maximum curvature rates for near target adjustments = 10.00 deg/100ft
Minimum curvature rates for near target adjustments = 0.10 deg/100ft
Distance of MWD survey sonde to TMD = 5.00 ft

Error Specifications

Constant vertical build rate performance error = -0.50 deg/100ft
Variable build rate error (as a percent of the desired build rate) = -5%
Fixed Toolface Error (enter in degrees clockwise) = 5.00 deg
Random inclination angle survey error (standard deviation) = 0.10 deg
Random azimuth angle survey error (standard deviation) = 0.30 deg

Table 5. Horizontal Trajectory Plans

Plan	Description	Section Length	Measured Depth ft	Inclination Angle deg	Azimuth degN	Dogleg Deg/hft	TVD Ft	Ht. Above Target ft
At	bit position	42	8,775.0	1.3	293.7	0.3	8,872.98	525.29
KOP	build curve	817.5	9,592.5	92.5	320	11.2	9,374.98	0
	horizontal	1,007.50	10,600.0	92.5	320	0	9,331.20	0
After 1st	bit position	5	9,243.8	54.1	319.9	10.7	9,272.43	123.21
Geologic	tangent	6	9,249.8	54.1	319.9	0	9,275.96	119.53
Target	build curve	376.8	9,626.6	91.8	320	10	9,384.41	0
Change	horizontal	973.4	10,600.0	91.8	320	0	9,353.95	0
After 2nd	bit position	5	9,371.9	66.2	319.8	10.2	9,336.75	59.6
Geologic	tangent	11.3	9,383.2	66.2	319.8	0	9,341.29	54.79
Target	build curve	252.6	9,635.7	91.5	320	10	9,389.67	0
Change	horizontal	964.3	10,600.0	91.5	320	0	9,364.52	0
After	bit position	5	9,997.0	91.4	319.7	0.2	9,380.28	-19.97
Faulted	adjust curve	107.8	10,104.8	102.2	319.9	10	9,367.51	-9.98
Target	adjust curve	107.1	10,211.9	91.5	320	10	9,354.75	0
Change	horizontal	388.1	10,600.0	91.5	320	0	9,344.63	0

Table 6. Directional Surveys from Horizontal Well Simulation

Measured Depth ft	Inclination Angle deg	Azimuth Angle dN	Dogleg Deg/hft	TVD ft	Vertical Section ft	Geologic Target #	Ht. Above Target ft
8,700.00	1.5	296.0		8798.00	0.00	1	600.00
8,733.00	1.4	295.0	0.3	8830.99	-5.08	1	567.32
8,801.03	3.8	307.0	3.6	8898.94	-2.11	1	499.23
8,832.60	7.3	312.1	11.1	8930.36	0.91	1	467.68
8,864.13	11.1	314.5	12.0	8961.48	5.91	1	436.34
8,895.88	14.7	316.3	11.6	8992.42	12.97	1	405.09
8,927.17	18.2	316.7	11.2	9022.43	21.82	1	374.70
8,957.90	21.8	317.3	11.7	9051.30	32.32	1	345.37
8,990.21	25.5	318.2	11.6	9080.88	45.28	1	315.22
9,021.12	28.9	318.5	10.7	9108.37	59.40	1	287.11
9,052.45	32.3	318.5	11.1	9135.34	75.33	1	259.45
9,083.48	35.9	318.1	11.6	9161.02	92.73	1	233.01
9,114.33	39.5	318.6	11.6	9185.43	111.58	1	207.78
9,146.26	43.0	318.5	11.0	9209.44	132.61	1	182.85
9,176.07	46.1	318.8	10.3	9230.69	153.51	1	160.69
9,208.54	49.9	319.1	11.9	9252.42	177.62	1	137.91
9,240.57	53.3	319.2	10.7	9272.31	202.72	1	116.93
9,269.86	56.4	319.3	10.4	9289.17	226.66	1	105.90
9,301.63	59.7	319.3	10.3	9306.00	253.61	2	88.24
9,334.32	62.9	319.7	9.9	9321.71	282.27	2	71.63
9,364.73	66.0	319.7	10.1	9334.83	309.70	2	57.64
9,395.84	68.0	319.6	6.5	9347.00	338.32	2	48.85
9,427.59	70.8	320.2	9.0	9358.18	368.04	3	36.89
9,458.72	73.9	320.2	10.0	9367.63	397.69	3	26.67
9,489.65	77.0	320.5	10.0	9375.42	427.62	3	18.11
9,523.02	80.3	320.1	10.0	9382.00	460.33	3	10.67
9,553.37	83.3	320.1	10.1	9386.33	490.37	3	5.56
9,585.88	86.7	320.4	10.5	9389.14	522.75	3	1.90
9,617.21	89.9	320.1	10.0	9390.06	554.06	3	0.17
9,647.76	90.9	319.5	3.9	9389.84	584.61	3	-0.41
9,678.89	91.6	319.8	2.3	9389.15	615.73	3	-0.53
9,709.44	91.9	320.1	1.3	9388.21	646.27	3	-0.39
9,740.27	91.9	319.9	0.4	9387.17	677.08	3	-0.15
9,771.68	91.8	320.2	1.1	9386.15	708.47	3	0.05
9,802.95	91.5	319.7	1.8	9385.24	739.73	3	0.14
9,833.50	91.3	319.7	0.9	9384.49	770.27	3	0.09
9,863.19	91.2	319.5	0.6	9383.86	799.95	3	-0.05
9,894.32	91.4	319.3	1.0	9383.15	831.07	3	-0.15
9,927.07	91.6	319.5	0.9	9382.30	863.81	3	-0.15
9,960.24	91.5	319.1	1.3	9381.40	896.97	3	-0.13
9,989.83	91.7	319.0	0.9	9380.56	926.54	3	-0.06
10,020.12	94.0	319.3	7.6	9379.04	956.79	3	-19.26
10,053.07	95.1	319.4	3.4	9376.42	989.63	4	-17.49
10,084.54	96.4	319.9	4.4	9373.25	1020.94	4	-15.14

Table 6 continued Directional Surveys from Horizontal Well Simulation

Measured Depth ft	Inclination Angle deg	Azimuth Angle dN	Dogleg Deg/hft	TVD ft	Vertical Section ft	Geologic Target #	Ht. Above Target ft
10,115.59	97.8	319.5	4.7	9369.40	1051.75	4	-12.09
10,147.34	98.8	320.1	3.6	9364.82	1083.17	4	-8.33
10,179.31	97.5	320.4	4.3	9360.30	1114.81	4	-4.64
10,210.08	95.4	320.2	6.7	9356.85	1145.39	4	-1.99
10,239.13	93.7	320.4	5.8	9354.54	1174.34	4	-0.43
10,271.16	92.7	319.8	3.6	9352.74	1206.32	4	0.54
10,301.09	92.0	320.3	3.1	9351.51	1236.23	4	0.98
10,333.06	91.3	320.3	2.0	9350.60	1268.18	4	1.06
10,364.61	90.4	319.9	3.3	9350.13	1299.73	4	0.71
10,395.68	91.1	319.9	2.2	9349.74	1330.80	4	0.29
10,425.41	91.2	319.7	0.8	9349.16	1360.52	4	0.09
10,456.38	91.3	319.6	0.7	9348.49	1391.48	4	-0.04
10,487.33	91.4	319.7	0.6	9347.74	1422.42	4	-0.10
10,518.48	91.5	319.7	0.4	9346.94	1453.56	4	-0.12
10,549.03	91.7	319.3	1.3	9346.09	1484.10	4	-0.06
10,579.76	91.7	319.7	1.4	9345.18	1514.81	4	0.05
10,595.00	91.7	319.8	0.7	9344.73	1530.05	4	0.10