ROD PUMPING DEVIATED WELLS

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ABSTRACT

More and more directional wells are being drilled to maximize hydrocarbon recovery and overcome environmental restriction. Today's state of art predictive software for rod pumping can be used to design and optimize rod pumping in deviated wells as well as vertical wells. Previously, traditional methods including wave equation techniques assume that the wellbore is vertical. Applying these methods to rod pumping in deviated wells and in unintentionally deviated (crooked) wells will result in substantial errors and cause inappropriate design. The new technique considers a deviation survey for the 3-D borehole trajectory and rod/tubing drag friction in the predictive design method. The paper examines a real case for a severely deviated well by using the new software, showing the best practices and optimization.

INTRODUCTION

A greater number of deviated wells are being drilled to increase production rates, and minimizes cost and ecological damage. Sucker rod pumping has been an efficient method in vertical wells and is becoming more and more common in deviated wells. During the last several decades, the deviated well was presumed to be a vertical well in the design and diagnosis of rod pumping well, which is based on the one-dimensional, viscous damped wave equation computerized model. Yet the model for vertical well is imprecise and not valid for a crooked-hole or a deviated well. In 1992, the 3-D deviated well model based on the modified version of wave equation was originally developed by Dr. Sam Gibbs and has been successfully incorporated into Lufkin Automation's rod pumping predictive and design program, called SROD[1]. Later on, Lufkin Automation developed and released a new version of the rod pumping diagnostic program, DIAG, which uses a similar model and algorithm as SROD for diagnosing deviated wells[2]. This paper presents the new wave equation methodology that incorporates both viscous friction and drags friction as well. A design procedure for intentionally deviated well is presented. Rod guide design is studied. Some other important concerns such as drag friction, guide friction coefficient, buckling, and dogleg servility are discussed. Finally, the effect of designing an optimum well-bore path before the well is drilled is examined.

MATHEMATICAL MODEL

Gibbs introduced a 3-D modified wave equation method to predict and design rod pumping in deviated wells.[1] The governing equation of motion that is solved to model rod pumping performance in deviated wells with rod dynamics, viscous friction and drag friction is expressed as follows:

$$\frac{\partial^2 u(s,t)}{\partial t^2} = v^2 \frac{\partial^2 u(s,t)}{\partial s^2} - c\frac{\partial u(s,t)}{\partial t} - \delta\ \mu(s)[Q(s) + T(s)\frac{\partial u(s,t)}{\partial s}] + g(s) \tag{1}$$

v represents acoustic velocity in the sucker rod. c represents the viscous damping coefficient, which models the effects of fluid viscous friction. $\mu(s)$ is the friction coefficient function, which provides for variation of friction coefficient along the rod string (due to bare rods and different types of rod guides). *Q(s)* and *T(s)* are functions, which depend on axial load and wellbore deviation. And g(s) is rod gravity effect. In the vertical well case, g(s) = constant and *Q(s) = T(s)*= 0; hence, Equation 1 reduces to the wave equation for vertical wells. A 3-D visualization of an element of the rod string as a free-body diagram in a deviated well is shown in Figure 1. Equation 1 is solved with the finite difference method subject to the complicated boundary conditions for the pump, surface unit and prime mover. The algorithm is developed in Lufkin Automation's predictive software called SROD.

It is a comprehensive computerized mathematical model program that is used to design rod-pumping system in vertical or deviated wells. The latest version of SROD features a simulation for hydraulic pumping units, such as DynaPump, with duel speeds for up-stroke and down-stroke. In addition, gas engine simulations have been improved, which includes the effects of higher fly wheel rotary inertia. Also, in deviated wells the placement of rod guides, the number of guides needed and their added weight to the rod string are automatically included.

SERIOUS CONSIDERATIONS IN DEVIATED WELL DESIGN

Rod Buckling. In general speaking, rod buckling can be caused by downhole rod frictions and faster pumping effect at fluid pound condition. Some unit geometry selections with faster trip on downstroke than upstroke may aggravate buckling tendency at fluid pound condition. Under-balanced units may also aggravate buckling problem.

The bottom portion of the rod string in pumping wells is always in compression from buoyancy on down-stroke, but buoyancy will not cause buckling. Buckling of a rod string immersed in a fluid is governed by the buckling tendency rather than the true load or axial load. The true load is useful for calculating rod loading base on stress range diagrams such as the API Modified Goodman Diagram. To determine if there is a tendency for rod buckling, one must carefully examine the buckling tendency at the bottom portion of the rod string. Example of true load (axial load) and buckling tendency are presented in Figure 7 or Figure 11. At depth of 10116 ft on Figure 11, negative true load = -2842 lbs, buckling tendency = -1006. The difference between them (-1836 lbs) reflects the fluid buoyancy effect.

Lea[5] introduced the following equation for critical load (lbs) necessary to buckle the rod.

$$F_{critical} = \sqrt[3]{0.795EI(\pi w)^2/144} \tag{2}$$

where I=moment of inertia of cross section = $\pi d^4/64$ (in^4)
E=elastic modulus of rod =30.5×10^5 (psi, for steel)
w= weight of rod in fluid = $w_{air}(1-0.128\gamma)$ (lbs/ft)

The criteria for buckling is that if the rod buckling tendency, which includes rod dynamics effect, is greater than $F_{critical}$, then the rods can be expected to buckle. However, Equation 2 is only applicable to vertical wells.

Rod Guide Design. In rod pumping wells the most expensive routine well servicing cost is the repair of tubing leaks. In many cases this wear is caused by side loads from a deviated well bore. Also, if rod buckling on the down-stroke is occurring rod/tubing wear can result, which is typically near the pump. Although there are a few options to reduce rod/tubing wear, rod guides along with keeping full pump condition could possibly be the most practical and the most cost-effective method of controlling rod buckling and rod/tubing wear problem. Basically, the rod guides act as sacrificial component to center the rod string in the tubing so that wear on the rods/couplings and the tubing is minimized. However, different rod guide design criteria exist in the industry for a long time. One method, named trial and error method, involves using statistical well failure database. A well with similar conditions and equipped with rod guides is applied to a well that is not currently installed with rod guides. If the failure frequency or rod guide wear is greater than predicted, then more guides are added the next time a failure occurs. Apparently, not only it is quite costly method but also it in general is limited by the amount of information in the database. Another methods based on buckling tendency and the static lab test are introduced in papers [3] and [4].

The rod guide design technology has been built into SROD application which can be integrated with the comprehensive wave equation solution, combining rod dynamics, rod and guide properties, side load, rod frictions (viscous and drag), rod buckling, various pump modes and actions, surface unit motion, and motor characteristics. Thus, rod guide design and buckling consideration is based on a real dynamic condition. The maximum side load on each rod is calculated and it is used to determine if the guide is needed and how many rod guides is needed. Based on the detail rod guide design, the program simplifies the rod guide design with a maximum of 10-rod sections for the purpose of practical field installation. Rod guides may be required in a vertical well too where buckling tendency is higher than tolerable. If so, buckling tendency plot is useful to perform rod guide design.

Several lab tests indicated that the asymmetrical molded guide spacing allowed higher critical Euler's load to buckle the rod than did the symmetrical molded guide spacing. Based on the lab observations, it is recommended that at least one molded guide should be closed to end of rod coupling by about 15 inches.[3]

Drag and Viscous Friction. Bare Rod Friction Coefficient is the coefficient of Coulomb friction between bare rod and tubing. Coefficient of friction (COF) times the side load (normal force between the tubing and a sucker rod) is equal to the frictional drag force on the sucker rod. The bare rod COF default value is 0.2. The COF depends on the type of materials that are rubbing, the roughness of the surface and the lubricity (oil versus water, etc.) This value can range from about 0.1 (oil lubricant and smooth surfaces) to about 0.3 (water lubricant and rough surfaces). The COF can be computed from dynamometer valve checks [6] or determined experimentally by trial and error. A trial and error solution requires a

dynamometer diagnostic analysis (DIAG) and selecting a COF for the design program (SROD) that results in good agreement between the design and diagnostic analysis.
Ratio of Guide Friction to Bare Rod Friction is used to adjust bare rod friction if rod guides are installed. When guides are added in the rod string, the relative friction effects of various guides are expressed as ratios to the frictional effects of bare rods. The friction ratio default value for molded guides is 1.5, which indicates that molded guides increase friction by 50% when compared to bare rods. The default value for wheeled guides is 0.1, which indicates wheeled guides will lower friction by 90% when compared to bare rods. For example, if the coefficient of friction for bare rods in a given well with a certain lubricity is 0.2, the coefficient of friction of molded guides in the same well will be simulated as 0.3 (1.5 * 0.2). Guide manufacturers should provide guide weight and friction coefficient data on specified guides based on lab tests.

Unfortunately, only a few guides have been tested in labs. Norris NorGlide® friction test results are shown in Table 1.
Another interesting phenomenon is that the number of guides per rod does not affect the axial load, drag and side load except for the guide weights, but the guide frictional property would have effect on these values.

Default viscous damping factors are 0.5 for up-stroke and 0.15 for down-stroke. These default values are typical for high gravity crude oil, say above 35 degrees API and high water cuts. Higher damping factors should be considered when guides are installed (more fluid turbulence and friction), especially in high volume pumping and low gravity oil.

Dogleg Severity. Dogleg severity, degrees per 100 feet, is based on the radius of curvature method, and expressed in rate of change in borehole inclination and azimuth with respect to measured depth. Dogleg severity is not used to calculate side or drag loads along the rod string. Dogleg severity is a useful guide in defining curvature of the well bore, but it is not particularly useful in deducing how to pump deviated wells. For example, a dogleg of 3.9 degrees per 100 feet results in side load of 395 lbs/rod near the surface (at 3309 ft), whereas, the same dogleg near the pump (at 9970 ft) causes a lower side load of 168 lbs/rod. See Figure 8 and Figure 10.

A typical deviation survey provides the following data: measured depth (feet), inclination (degrees), azimuth (degrees), true vertical depth (feet) N-S and E-W rectangular coordinates (feet) and dogleg severity (degrees/100 feet). Deviation data required by SROD is measured depth, inclination, and azimuth. SROD calculates true vertical depth, N-S and E-W rectangular coordinates, and dogleg severity. Since the radius of curvature method is commonly used, dogleg severity calculated by SROD should closely match dogleg severity shown in the survey. Any difference indicates an error in input data.

APPLICATION TO WELL DESIGN

Deviated wells can be categorized into unintentionally deviated (crooked) and intentionally deviated. An unintentional deviated well is usually not in a plane but a 3-D spatial curve. Such a well is demonstrated in Figure 2. An intentionally deviated well usually lies on a vertical or near vertical plane. Such a well is shown in Table 2, Base Case Design and Performance.

This well is severely deviated with a pump setting of 11076 ft. In order to perform a deviated well analysis, the deviation survey must be input to the program. The input data is measure depth, inclination and azimuth. Figure 3 is a 3-D well-bore path. Figure 4 through 6 show well-bore views looking north, east and (down) plan. Table 2 shows the predicted performance as a base case. Rod guide design has been simplified into 10 rod sections (also see table2). Rod string weight per foot is automatically adjusted to include the weight of the guides.

As seen in base case design, gearbox is overloaded 11.7%, unit structure is overloaded 3.4%, and the 1 inch ultra high strength rods are overloaded 15% based on a service factor of 0.9. The buckling tendency is 200 lbs, which is caused by pump friction. See Figure 7. Complete pump fillage is assumed in the design.

The current installation requires 13 guides per rod (interval 2) and 15 guides per rod (interval 3), which is not practical. To improve performance the molded guides in intervals 2 and 3 are replaced with wheeled guides. The predicted performance is shown on Table 3. Equipment loading is substantially reduced, but the 1 inch rods are still overloaded 4%. The operator desires to increase displacement from 197 BPD to 220 BPD to compensate future pump wear or possible food response. An increase in pump displacement with existing equipment would be difficult to achieve because of high equipment loads. The best solution to increase pump displacement to 220 BPD without increasing equipment loading is to replace the 1-1/2 inch pump with a 1-1/4 inch pump and increase pumping speed from 5.5 SPM to 6.83 SPM. Table 4 is a performance report for the improved installation. Gearbox loading is reduced to 77.5% and rod loading is reduced to 98% with a 0.9 service factor. With the faster pumping speed the buckling tendency remains constant at 200 lbs from pump friction only. Figures 8 to 10 are side load, drag load and dogleg severity plots, respectively.

However, if the well is over-displaced and a fluid pound develops (85% pump fillage) a buckling tendency as high as 1006 lbs is predicted 960 feet above pump. See Figure 11.

The region subject to buckling extends over the entire 7/8 inch rods at the bottom and peaks 1006 lbs in the ¾ inch rods. Equation 2 gives:
$w=1.634\times(1-0.128)=1.425$ lbs/ft
$I=\pi d^4/64=0.02878$ (in^4)
$$F_{critical}=\sqrt[3]{0.795EI(\pi w)^2/144}=38\ (lbs) \ll 1006\,(lbs)\,.$$
Obviously, 1006 lbs buckling tendency would buckle ¾ inch rods. To minimize rod buckling with a fluid pound sinker bars should be considered. The heavy sinker bars will reduce the buckling tendency. Also, pump-off control to minimize pounding fluid is normally recommended.

OPTIMIZED WELLBORE PATH

Another important design consideration involves selecting an optimum well-bore path before the well is drilled. The optimum path will minimize side loads and rod drag, which will reduce all equipment loads, power consumption and rod/tubing wear. Optimum well-bore paths will exist and the solution can be sought by trial and error. Such an example is given in Figure 12. The first well-bore involves a kick-off at 4000 ft, and abruptly builds to an inclination of 32° with a max angle building rate of $3^{\circ}/100$ ft. It is predicted that monthly power charge for this well-bore is $1571 per month, and the rods and unit are overloaded. See Table 5. An improved well-bore path shows an angle building rate of $1^{\circ}/100$ ft until the maximum inclination of 38° and then reaches to the target at an inclination of 14°. Power cost for this improved path is $1222/month (29% savings), pump capacity is increased 23% and equipment is loading is reduced substantially. Lower equipment loads and reduced rod/tubing wear (lower side loads) will greatly reduce repair and maintenance costs. Meanwhile, 11 guides per rod are required for taper 3 before the wellbore path is optimized. After optimization of the wellbore path, only 3 guides per rod are needed for this section. When the well path is carefully planned and controlled, the costs in power, repair and maintenance can be reduced and some problems related to deviated well can be eliminated. Some deviated wells thought to be infeasible with rod pumping equipment can now be lifted.

CONCLUSIONS

1. A modified version of the wave equation method has been developed, which considers rod/tubing side loads and drag for deviated wells.
2. Buckling tendency is a serious consideration in the rod pumping design, especially for deviated wells. Measures can be taken to reduce buckling tendency by maintaining good pump fillage, smaller pump, slower speed, adding sinker bar and selecting the proper unit geometry.
3. Smaller bore pumps can be effectively used to reduce side/drag loads.
4. Optimum well-bore paths exist that will reduce power consumption and equipment loads (reduce repair and maintenance costs).
5. Dogleg severity is a useful guide in defining curvature of a well bore, but it is not particularly useful in deducing how to pump deviated wells. A dogleg near the surface results in much higher side loads than the same dogleg near the pump.

ACKNOWLEDGMENT

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Table 1
NorGlide® NorGlide® Specifications

Coefficient of Friction of RAMEX® UHMW			
	Coefficient of Friction		
Sliding Surface (Ramex®)	**Sliding Speed**	**Static**	**Kinetic**
On Itself	2 in./min	0.35	0.25
On chrome-plated steel	2 in./min	0.23	0.17
On stainless steel	2 in./min	0.25	0.14
On cold-rolled steel	2 in./min	0.31	0.18
On brass	2 in./min	0.21	0.15

Table 2
Base Case Design and Performance

SROD v6.0 - PREDICTION OF ROD PUMPING SYSTEM PERFORMANCE

WELL NAME	: A Deviated Well	DATE/TIME	: 1/7/2005 11:02:55 AM
ANALYST	:	COMPANY	: Oil Company
DATA FILE	: SWPSC Example.inp6 (ALLMOLDED)	WELL TYPE	: Deviated

** PRIME MOVER **

G.E. 100 HP KOF

Speed Variation (%)	: 15.5	Cyclic Load Factor	: 1.741
Power Required (hp)	: 92	Motor Load (% of Rating)	: 92
Sheave Ratio (Unit/ Prime Mover)	: 7.464		

** PUMPING UNIT **

LUFKIN M1280-427-216 WITH MRO CRANKS (CC'WISE)

Actual Max Load (lbs)	: 44144	Actual Min Load (lbs)	: 14082
Pumping Speed (spm)	: 5.48	Max Load (% of Rating)	: 103.4
Polished Rod Power (hp)	: 47.5	Computed Surface Stroke (in)	: 215.9

** GEAR REDUCER **

	EXISTING	IN BALANCE
Max Torque (m in-lbs)	1459.5	1429.8
Min Torque (m in-lbs)	-957.4	-940
Counterbalance (m in-lbs)	4196.8	4178.8
Effective Balance (X100 lbs)	373.2	371.3
Percent of Reducer Rating	114	111.7

** ROD STRING **

	Diameter (in)	Length (ft)	Rod Type	Rod Loading	Guides
1)	1 *	2936	NORRIS 97	115	M (6)
2)	1 *	150	NORRIS 97	79	M (13)
3)	0.875	780	NORRIS 97	106	M (15)
4)	0.875	730	NORRIS 97	89	M (4)
5)	0.875	270	NORRIS 97	81	M (5)
6)	0.875	1200	NORRIS 97	77	M (5)
7)	0.75	2580	NORRIS 97	89	N (0)
8)	0.75	300	NORRIS 97	64	M (4)
9)	0.75	1530	NORRIS 97	61	M (4)
10)	0.875	600	NORRIS 97	33	M (3)

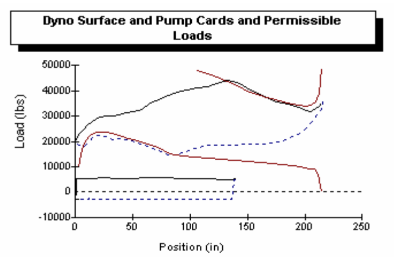
* Requires slimhole couplings.

Service Factor for Steel Rod	: 0.9		
Max Stress @ surface (psi)	: 56078	Min Stress @ surface (psi)	: 18057

** DOWNHOLE PUMP **

Bore Size (in)	: 1.5	Setting Depth (ft)	: 11076
Tubing Stretch (in)	: 0.9	Lost Displacement (bpd)	: 1
Pump Intake Pressure (psi)	: 100	Pump Spacing Guide (in)	: N/A
Tubing Size (in)	: 2.875	Tubing Anchor Location (ft)	: 10578
Tubing Gradient (psi/ft)	: 0.427	Pump Fillage (%)	: 99

	Stroke (in)	BPD at 100% eff.	BPD at 80% eff.
Gross:	139.6	201 (24h/d)	160 (24h/d)
Net:	137.1	197 (24h/d)	158 (24h/d)



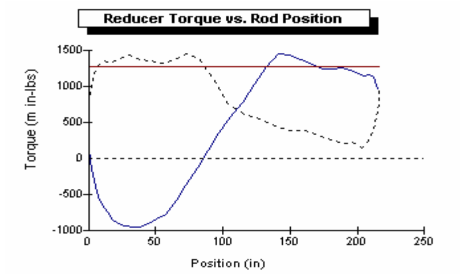


Table 3
Wheeled and Molded Guide Design and Its Performance

SROD v6.0 - PREDICTION OF ROD PUMPING SYSTEM PERFORMANCE

WELL NAME	: A Deviated Well	DATE/TIME	: 1/7/2005 2:03:29 PM
ANALYST	:	COMPANY	: Oil Company
DATA FILE	: SWPSC Example.inp6 (WHEELMOLDED)	WELL TYPE	: Deviated

** PRIME MOVER **
G.E. 100 HP KOF

Speed Variation (%)	: 13.8	Cyclic Load Factor	: 1.822
Power Required (hp)	: 81	Motor Load (% of Rating)	: 81
Sheave Ratio (Unit/ Prime Mover)	: 7.505		

** PUMPING UNIT **
LUFKIN M1280-427-216 WITH MRO CRANKS (CC'WISE)

Actual Max Load (lbs)	: 41282	Actual Min Load (lbs)	: 14286
Pumping Speed (spm)	: 5.49	Max Load (% of Rating)	: 96.7
Polished Rod Power (hp)	: 40	Computed Surface Stroke (in)	: 215.9

** GEAR REDUCER **

	EXISTING	IN BALANCE
Max Torque (m in-lbs)	1283.1	1237.4
Min Torque (m in-lbs)	-909.1	-930.7
Counterbalance (m in-lbs)	4004.2	4034.6
Effective Balance (X100 lbs)	352.7	355.9
Percent of Reducer Rating	100.2	96.7

** ROD STRING **

	Diameter (in)	Length (ft)	Rod Type	Rod Loading	Guides
1)	1 *	2936	NORRIS 97	104	M (6)
2)	1 *	150	NORRIS 97	71	W (2)
3)	0.875	780	NORRIS 97	96	W (3)
4)	0.875	730	NORRIS 97	88	M (4)
5)	0.875	270	NORRIS 97	79	M (5)
6)	0.875	1200	NORRIS 97	75	M (5)
7)	0.75	2580	NORRIS 97	88	N (0)
8)	0.75	300	NORRIS 97	63	M (4)
9)	0.75	1530	NORRIS 97	59	M (4)
10)	0.875	600	NORRIS 97	33	M (3)

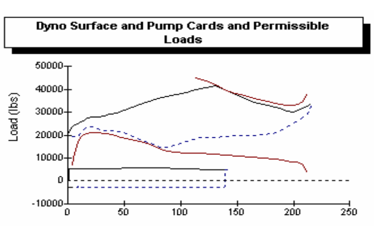
* Requires slimhole couplings.

Service Factor for Steel Rod	: 0.9		
Max Stress @ surface (psi)	: 52435	Min Stress @ surface (psi)	: 18316

** DOWNHOLE PUMP **

Bore Size (in)	: 1.5	Setting Depth (ft)	: 11076
Tubing Stretch (in)	: 0	Lost Displacement (bpd)	: 0
Pump Intake Pressure (psi)	: 100	Pump Spacing Guide (in)	: N/A
Tubing Size (in)	: 2.875	Tubing Anchor Location (ft)	: 11076
Tubing Gradient (psi/ft)	: 0.427	Pump Fillage (%)	: 99

	Stroke (in)	BPD at 100% eff.	BPD at 80% eff.
Gross:	140.7	203 (24h/d)	162 (24h/d)
Net:	139.1	200 (24h/d)	160 (24h/d)



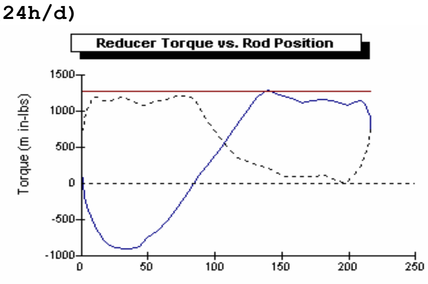


Table 4

Improved Design and Performance

SROD v6.0 - PREDICTION OF ROD PUMPING SYSTEM PERFORMANCE

WELL NAME	: IB8	DATE/TIME	: 1/7/2005 2:54:59 PM
ANALYST	: Paul	COMPANY	: Vintage
DATA FILE	: SWPSC Example.inp6 (125 PUMP DIA)	WELL TYPE	: Deviated

** PRIME MOVER **

G.E. 100 HP KOF

Speed Variation (%)	: 13.7	Cyclic Load Factor	: 1.496
Power Required (hp)	: 82.7	Motor Load (% of Rating)	: 82.7
Sheave Ratio (Unit/ Prime Mover)	: 5.983		

** PUMPING UNIT **

LUFKIN M1280-427-216 WITH MRO CRANKS (CC'WISE)

Actual Max Load (lbs)	: 39426	Actual Min Load (lbs)	: 13087
Pumping Speed (spm)	: 6.83	Max Load (% of Rating)	: 92.3
Polished Rod Power (hp)	: 49.2	Computed Surface Stroke (in)	: 215.9

** GEAR REDUCER **

	EXISTING	IN BALANCE
Max Torque (m in-lbs)	1087.4	991.9
Min Torque (m in-lbs)	-612.8	-686.9
Counterbalance (m in-lbs)	3718.6	3821.7
Effective Balance (X100 lbs)	322.2	333.2
Percent of Reducer Rating	85	77.5

** ROD STRING **

(Counts/rod)	Diameter (in)	Length (ft)	Rod Type	Rod Loading	Guides
1)	1 *	2936	NORRIS 97	98	M (5)
2)	1 *	150	NORRIS 97	68	W (2)
3)	0.875	780	NORRIS 97	90	W (3)
4)	0.875	730	NORRIS 97	83	M (4)
5)	0.875	270	NORRIS 97	74	M (5)
6)	0.875	1200	NORRIS 97	71	M (5)
7)	0.75	2580	NORRIS 97	81	N (0)
8)	0.75	300	NORRIS 97	56	M (3)
9)	0.75	1530	NORRIS 97	52	M (3)
10)	0.875	600	NORRIS 97	26	M (3)

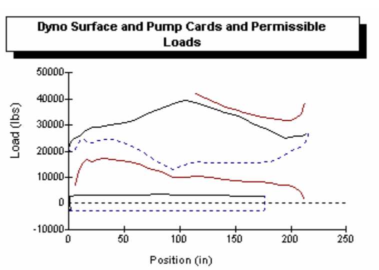
* Requires slimhole couplings.

Service Factor for Steel Rod	: 0.9		
Max Stress @ surface (psi)	: 50072	Min Stress @ surface (psi)	: 16790

** DOWNHOLE PUMP **

Bore Size (in)	: 1.25	Setting Depth (ft)	: 11076
Tubing Stretch (in)	: 0.6	Lost Displacement (bpd)	: 1
Pump Intake Pressure (psi)	: 100	Pump Spacing Guide (in)	: N/A
Tubing Size (in)	: 2.875	Tubing Anchor Location (ft)	: 10578
Tubing Gradient (psi/ft)	: 0.427	Pump Fillage (%)	: 100

	Stroke (in)	BPD at 100% eff.	BPD at 80% eff.
Gross:	176.6	220 (24h/d)	176 (24h/d)
Net:	176	219 (24h/d)	175 (24h/d)



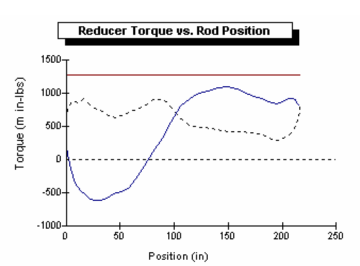


Table 5

Performance Comparison for Different Wellbore Path Selection (Before and After Optimization)

	Before Wellbore Path Optimized	After Wellbore Path Optimized
Motor Load (%):	62	53
Structure Load (%):	122	104
Reducer Load (%):	93	83
Rod Load of 1" rod (%):	124	95
Net BPD:	288	354
Power Cost ($/month):	1571	1222
Number of Guides for 3000' of 1" rod	0	0
Number of Guides for 950' of 7/8" rod	0	0
Number of Guides for 2600' of 7/8"	11	3
Number of Guides for 3550' of ¾"	4	4

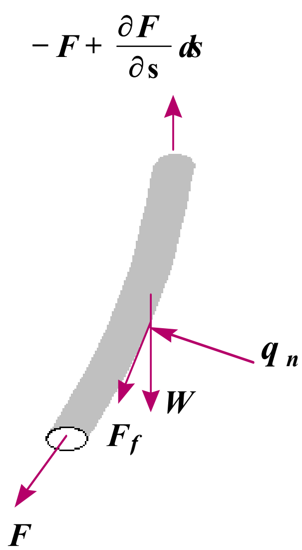


Figure 1- Schematic of Rod Element in a Deviated Well (3-D model)

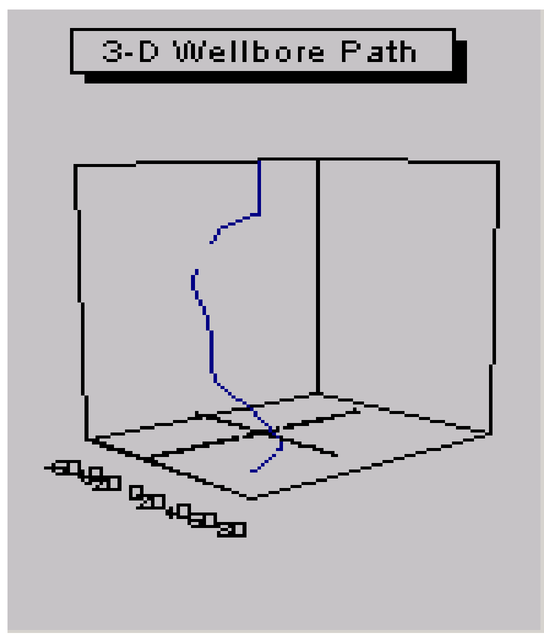


Figure 2 - An Unintentional Deviated Wellbore Path

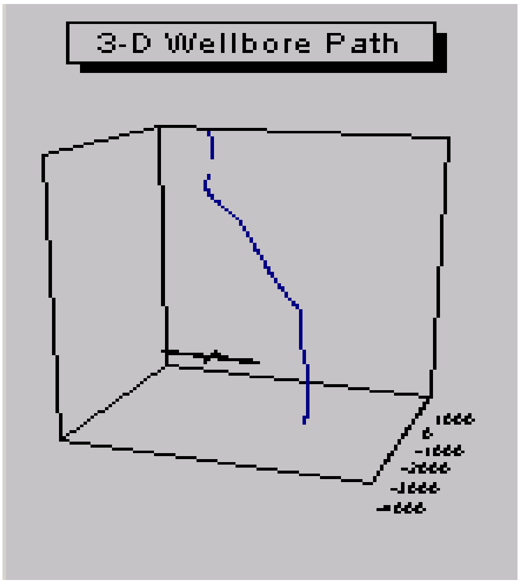


Figure 3 - 3-D Well Bore Plot for the Studied Well

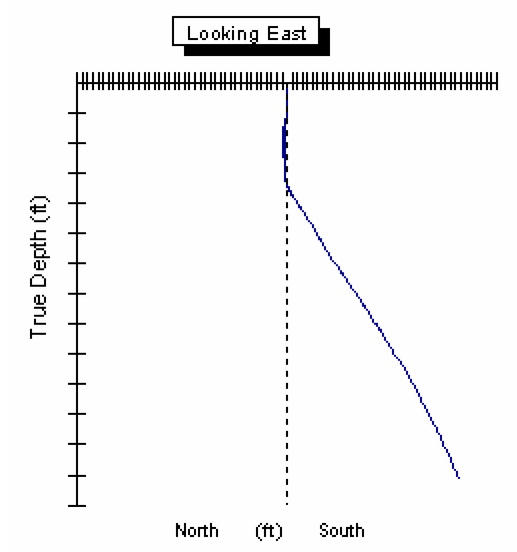


Figure 5 - Looking East Borehole Path

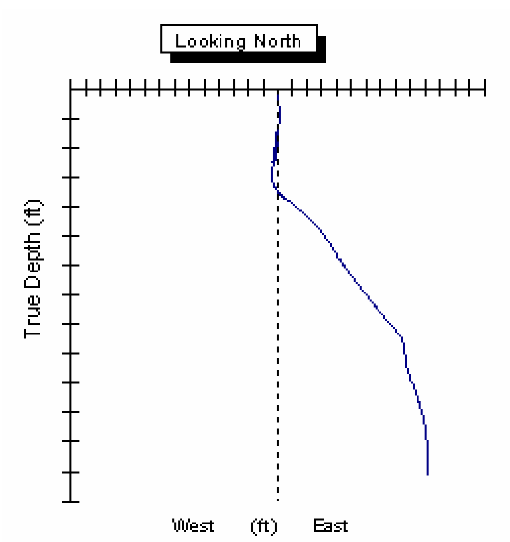


Figure 4 - Looking North Borehole Path

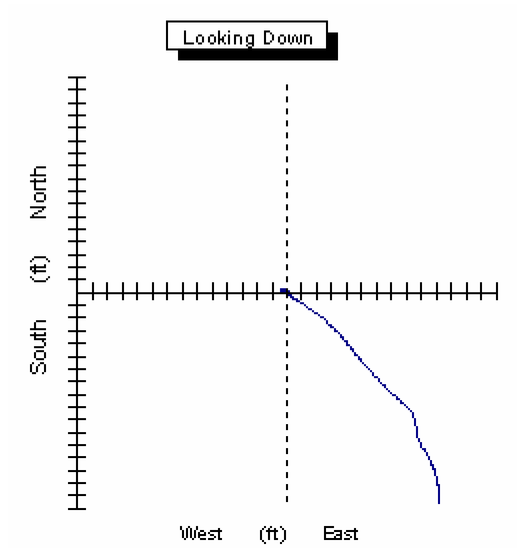


Figure 6 - Looking Down Borehole Path

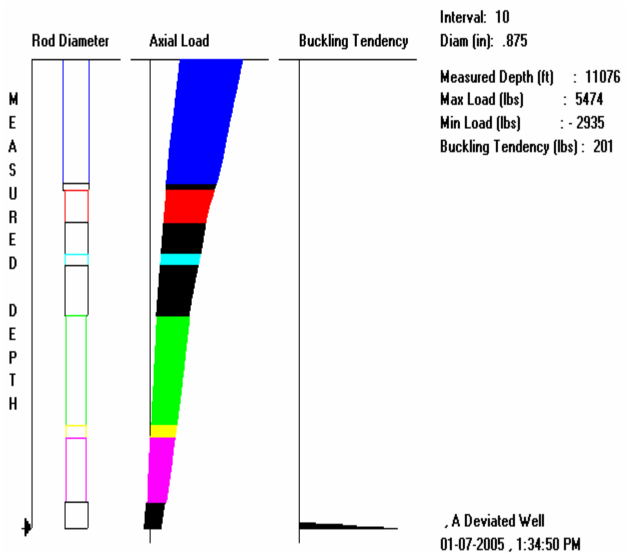


Figure 7 - Axial Load and Buckling Tendency Plot

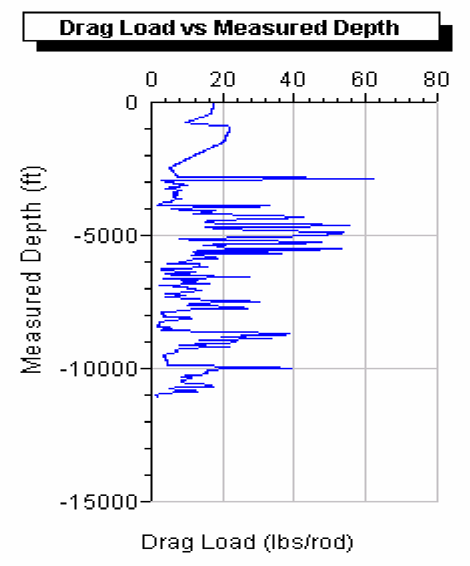


Figure 9 - Drag Load Plot

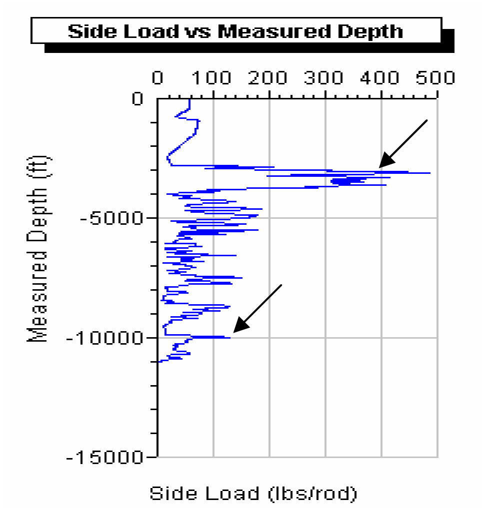


Figure 8 - Side Load Plot

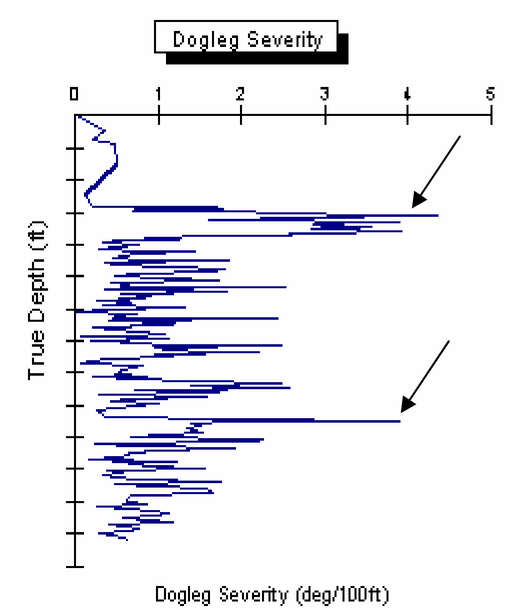


Figure 10 - Dogleg Severity Plot

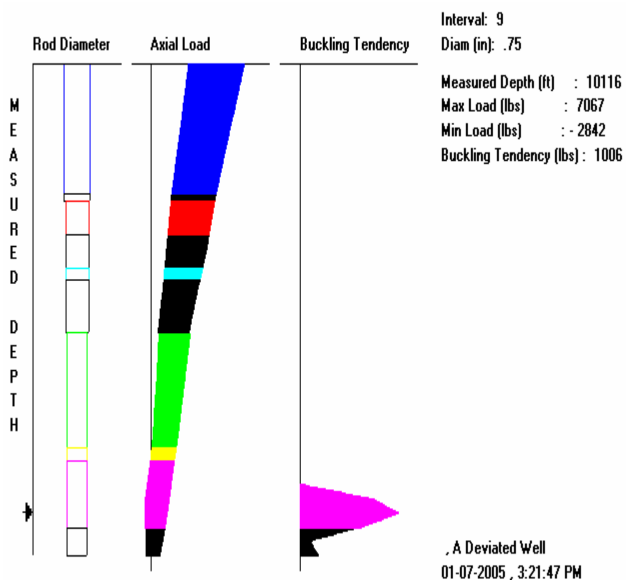
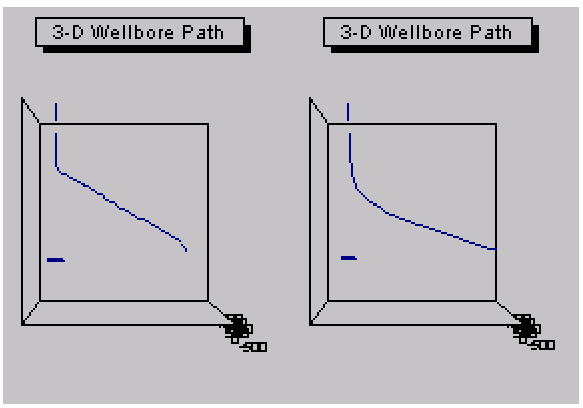


Figure 11 - Axial Load and Buckling Tendency for the Well with Fluid Pound



Before Optimization After Optimization

Figure 12 - Performance Comparisons for Different Wellbore Path Before and After Optimization