A COMPARISON OF THE PERFORMANCE OF LINEAR ACTUATOR VERSUS WALKING BEAM PUMPING SYSTEMS

Thomas Beck and Ronald Peterson
Unico, Inc.

ABSTRACT
Rod pumping units have historically used a crank-driven walking beam to provide a reciprocating motion for oil and gas production. Several geometries have evolved over the years to produce desirable polished rod motion profiles and gearbox torque loads. These mechanical systems are limited in their ability to manipulate the motion profile, and a given pumping unit profile is forever fixed by the selected geometry.

Hydraulic cylinder linear actuators became available a number of years ago for reciprocating rod pumping of oil and gas wells. Electrically driven rack-and-pinion linear actuators have also been recently developed for rod pumping applications. These hydraulic and electric linear pumping units share some common advantages over mechanical pumping units that are examined in this paper.

TRANSPORTATION AND INSTALLATION LOGISTICS

Linear pumping units are generally less massive than comparable walking beam units and can be mounted directly to the wellhead. The cost savings on site preparation, transportation logistics, and equipment installation can be substantial.

Figure 1 shows a dimension diagram for conventional pumping units, and Figure 2 gives the pumping unit stroke, height, width, and length dimensions. Pumping unit dimensions obviously grow with stroke length. Table 1 shows that height, width, and length ratios relative to stroke improve with pumping unit size. Figure 3 shows a simplified dimension diagram of linear rod pumps with the associated dimensions shown in Figure 4.

Linear rod pumps with strokes up to 68 inches are rack-and-pinion units driven by electric motors, and the 120-inch stroke unit is an hydraulic-cylinder-based unit. The relative heights of the linear units are similar to walking beam pumping units, but the length and width are considerably smaller. Weights of the various units are difficult to compare, but linear rod pumps often weigh considerably less than mechanical pumping units. The linear rod pumps have shipping weights in the range of 1,000 to 4,000 pounds, depending on stroke length.

The relatively small dimensions and weight of linear pumping units can dramatically affect transportation and installation logistics. Transportation of mechanical pumping units generally involves one or more flat bed trailers of equipment like that shown in Figure 5. Getting that equipment into remote hilly regions can be a struggle. As can be seen in Figure 6, the smaller linear pumping units can actually be transported in the back of a pickup truck.

The installation of linear rod pumps can generally be completed in less than one day using a service rig, picker truck, or front-end loader. The linear rod pumps with strokes up to 144 inches and polished rod loads up to 30,000 pounds have successfully used direct mounting to the casing as shown in Figure 7. Direct tubing mounts shown in Figure 8 can be used for the smaller linear pumping units. The tubing mount is similar to that used with progressing cavity pumps like that shown in Figure 9, and it simplifies the transition to rod pumping that often proves necessary in coal-bed methane applications.

The small size and direct wellhead mount not only minimize ground disturbance but have beneficial effects on aesthetics and safety as well. Figures 10 through 12 show linear rod pump installations in Texas, New Mexico, and Venezuela prior to the removal of the walking beam pumping units they replaced. These figures graphically illustrate the relative size of the linear actuator versus walking beam pumping technologies.

These figures also show the potential improvement in well-site appearance for environmentally sensitive areas. Sound levels for linear rod pumps also tend to be substantially less than the mechanical pumping units. Since the only moving part of the linear rod pump is the polished rod, it is substantially safer than walking beam pumps, which have numerous moving components and associated dangerous pinch points. A simple screen around the mounting base can be used to eliminate access to any moving parts and the need for protective fencing or enclosures.

The relatively large weights of walking beam pumping units compared to linear rod pumps is due, in large part, to the counterbalance weight and its associated mechanism. The electric linear rod pumps can often be operated without counterbalance due to the relatively shallow depth of the wells appropriate for that technology. Electric units can also make use of drive systems that feed downstroke regenerative energy back to the power line.

Air cylinders are also available on electric units like that shown in Figure 13 to provide a counterbalance effect. These cylinders can be designed to serve a dual purpose of providing both counterbalance effect and casing gas compression. That compression can be used to boost casing pressure at the well site in CBM applications and lower backside pressure to improve production on both oil and gas wells. A counterbalance effect can also be achieved on hydraulic units using nitrogen accumulators.

PUMPING UNIT ANALYZERS AND SIMULATORS

Commercial pumping unit analyzers such as the Rodstar program support linear pumping units like the Rotaflex® and DynaPump units. Those modern analysis programs include pumping unit simulation capability. Improvements in computer processing capacity and simulation techniques provide pump performance analysis that closely matches field test results.

Figure 14 shows the dynamometer cards measured in the field on a Rotaflex® pumping unit. As can be seen in Figure 15, the dynamometer card simulation from a Rodstar analysis program is nearly identical to the measured field results. Similar analysis programs exist for electric linear rod pumps. These analysis programs include a simulator that not only runs on a desktop computer but is also built into the controllers to allow instantaneous comparison of measured and simulated results, such as that shown in Figure 16.

PUMPING UNIT MOTION PROFILES

Linear actuators also have an important advantage in their ability to provide independent control of up and down stroke peak velocities as well as the shape of the velocity profile. Controlling the velocity profile allows increased pump cycle rate and associated production without exceeding rod fall velocity limits. An analysis program was developed to compare the performance of the linear versus both conventional (Class I) and phased-crank (Class III) pumping units.

The motion profile of the mechanical pumps can be calculated from their API dimensions using the method described in the API standard 11E, *Specification for Pumping Units*, November 1, 1994. The motion profile for a linear pump generally has a trapezoidal shape with controlled acceleration through the endpoints. The analysis program input parameters includes mechanical pumping unit dimensions and linear pump acceleration time as a percentage of the pump cycle time.

API dimensions for 100-inch stroke pumping units were used as Pumping Unit Parameters in the analysis of both Class I and Class III geometries. A 5,000-foot-deep well with a 76 taper rod design and a 1.500-inch insert pump was used as System Input Parameters for the analysis for pumping units running at 10 spm. The analysis program produces a number of familiar Calculated Parameters as well as graphical displays of rod velocity and position profiles versus time for both linear actuator and walking beam pumping units.

The linear rod pump trapezoid profile will generally have lower peak speeds than the cycloid profile of a walking beam pumping unit due to the ability of the pump to quickly change direction. The faster the acceleration rate through the endpoints or corners, the less speed is required down the straightaway to cover the same rod stroke. This capability of the linear rod pump to cover greater distance for any given peak speed can be used to increase the pump stroking rate and production without exceeding rod fall velocity limits.

The analysis program shows graphical results for both linear actuator and walking beam pumping units operating at the same stroking rate and polished rod stroke. Those charts show matched polished rod stroke, but linear rod pump velocities that are generally lower than those of the mechanical pumping unit. Linear rod pump velocity and position profiles are also shown assuming the peak up and down stroke speeds are the same as those of the mechanical pumping unit. That set of charts shows matched peak rod speeds, but linear rod pump polished rod strokes that are generally larger than those of the mechanical pumping unit.

Figures 17 through 19 show the results for a conventional pumping unit with Class I geometry along with the results for a linear pumping unit with acceleration times of 75% and 25% of the total cycle time. Figures 20 through 22 show the results for a phased-crank pumping unit with Class III geometry along with the results for a linear pumping unit with acceleration times of 75% and 25% of the total cycle time. The pump speed (Np), plunger stroke (Sp), and fluid production (Qp) are shown in the Calculated Parameters for the mechanical sucker-rod pump (SRP). The pump speed (Npe), plunger stroke (Spe), and fluid production (Qpe) are also shown for the linear rod pump (LRP) for the same up and down stroke peak speeds as the mechanical pump.

The analysis results are also shown in a Performance Comparison table. As can be seen from the charts and the table, linear rod pump acceleration times of 75% of the pump cycle time gives results nearly identical to the mechanical rod pump. This implies the mechanical rod pump spends about 75% of its total cycle time accelerating or decelerating. Decreasing the acceleration time allows the linear rod pump to increase its pumping rate and associated production. At an acceleration percentage of 25% of the cycle time, the linear actuator pump can produce 45% more fluid than a comparable walking beam pump.

DYNAMIC PROFILE MANIPULATION

Linear actuator pumping units also have an important advantage in their ability to provide closed-loop control of polished rod load as well as programmable control of polished rod motion profile. The relatively low mass of linear actuator mechanisms allows nearly instantaneous adjustment of polished rod velocity and load. Velocity profile control can also be used to reduce gas interference and fluid pound. Rod stroke position can be controlled to provide periodic pump tapping to overcome downhole pump problems. Polished rod load control can be used to limit minimum rod load, eliminate bridle separation, and damp rod load oscillation.

Fluid production from high water cut wells cannot generally be increased beyond that associated with the pumping unit speed that causes the pump fill to fall below 100%. Further increases in speed beyond that point would be accompanied by a proportionate fall in pump fill. In other words, there is not much benefit from trying to reduce pump fill significantly below 100%. Wells with foamy casing fluid columns that are producing some of the gas up the tubing can see significant production increases by pumping at relatively low pump fills. For example, the optimum pump fill for some of the wells producing heavy foamy oils in Venezuela is approximately 60%

While there may be production benefits from running at reduced pump fills, there is a penalty to pay due to fluid pound as the plunger strikes the fluid. The low inertia associated with linear rod pumps allow the motion profile to be manipulated to get the best of both worlds. Figure 23 shows the polished rod and pump plunger velocities for a linear rod pump operating with a 75% pump fill. The vertical velocity scale on the chart is in inches per second and the horizontal time scale is in 40 millisecond clock ticks. Figure 24 shows the same pump fill and cycle rate with a soft landing feature enabled. That feature provides a reduced speed on the down stroke until the plunger has contacted the fluid and then increases the speed to make up for lost time. In this example, the speed of the plunger at the point of contact with the fluid has been reduced from about 22 inches per second to 6 inches per second.

The fast acceleration of linear rod pumps that provide increased pump cycle rate and associated production has the potential to increase rod load oscillation. The magnitude of those oscillations is primarily determined by the ratio of the pump cycle rate to the natural frequency of the rod string rather than the detailed shape of the velocity profile. Regardless of the source of the load oscillation, it can be significantly damped by the closed-loop rod load control capability of the linear rod pump system.

Load damping and limiting can be applied to both the up and down stroke loads to minimize rod parts and reduce tubing wear. Figure 25 shows the rod and pump velocity for a fixed velocity profile. The vertical velocity scale on the chart is in inches per second and the horizontal time scale is in 40 millisecond clock ticks. Figure 26 shows the associated surface and downhole dynamometer cards. The vertical force scale on the chart is in pounds and the horizontal position scale is in inches.

The charts in Figures 27 and 28 show the improvement that can be achieved using the closed-loop rod load damping and limiting. In this example, reduction in peak downhole pump speed from 25 inches per second to 15 inches per second using patented rod load damping can provide a significant reduction in gas interference and gas locking. The reduction in peak polished rod load can help reduce rod parts and tubing wear. Minimum rod load limiting can be particularly useful in preventing bridle separation in difficult-to-produce wells. Limiting minimum rod load to avoid rod compression also reduces tubing wear.

CONCLUSIONS

Pumping units based on electric or hydraulic linear actuators have significant advantages over walking beam type pumping units including relatively small size and weight, simple transportation and installation, inherent safety and aesthetics, low noise pollution, enhanced production rates, and dynamic load management.

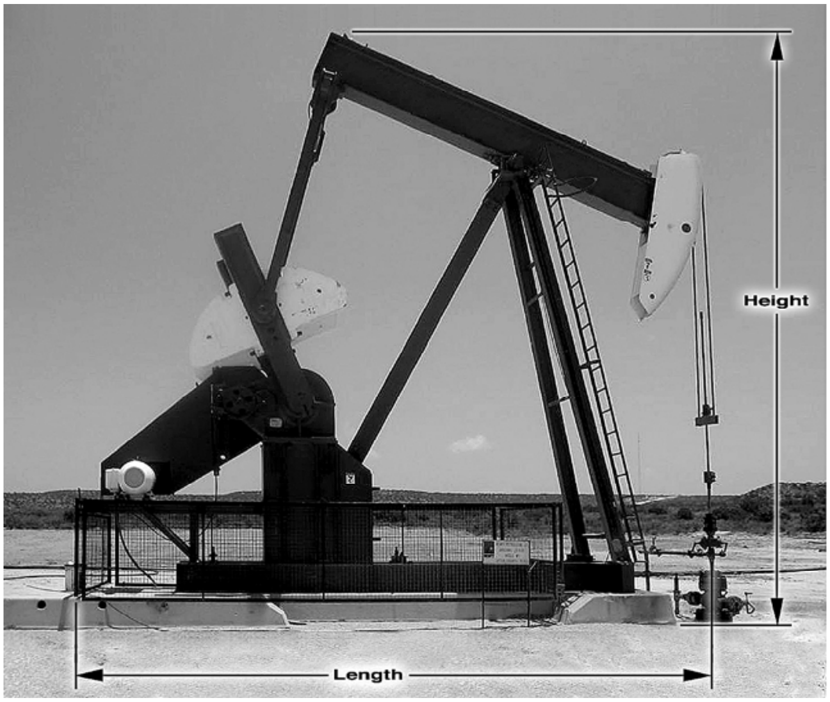


Figure 1— Conventional Pumping Unit Dimension Diagram

Stroke Inches	Height Inches	Height/ Stroke	Width Inches	Width/ Stroke	Length Inches	Length/ Stroke
36.00	129.00	358%	47.00	131%	213.00	592%
48.00	158.00	329%	51.00	106%	229.00	477%
54.00	172.00	319%	58.25	108%	251.50	466%
64.00	191.50	299%	66.25	104%	276.50	432%
86.00	252.00	293%	66.25	77%	346.00	402%
100.00	295.00	295%	70.50	71%	381.50	382%
120.00	349.00	291%	78.50	65%	441.50	368%
144.00	398.00	276%	87.50	61%	490.63	341%
168.00	421.50	251%	98.50	59%	520.50	310%
192.00	464.00	242%	106.00	55%	524.06	273%
240.00	545.00	227%	120.00	50%	557.50	232%

Figure 2— Conventional Pumping Unit Dimensions

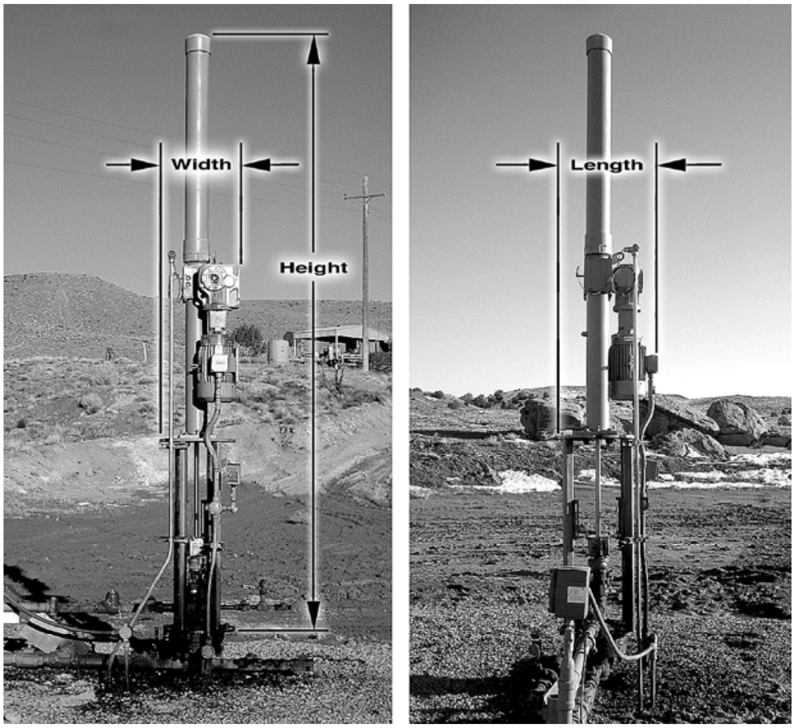


Figure 3— Linear Rod Pump Dimension Diagram

Stroke Inches	Height Inches	Height/ Stroke	Width Inches	Width/ Stroke	Length Inches	Length/ Stroke
32.00	156.00	488%	22.00	69%	27.00	84%
44.00	180.00	409%	22.00	50%	27.00	61%
56.00	204.00	364%	22.00	39%	27.00	48%
68.00	228.00	335%	22.00	32%	27.00	40%
120.00	300.00	250%	26.00	22%	26.00	22%

Figure 4— Linear Rod Pump Dimensions and Weights

Figure 5—Walking Beam Pumping Unit Transportation

Figure 6—Linear Rod Pump Transportation

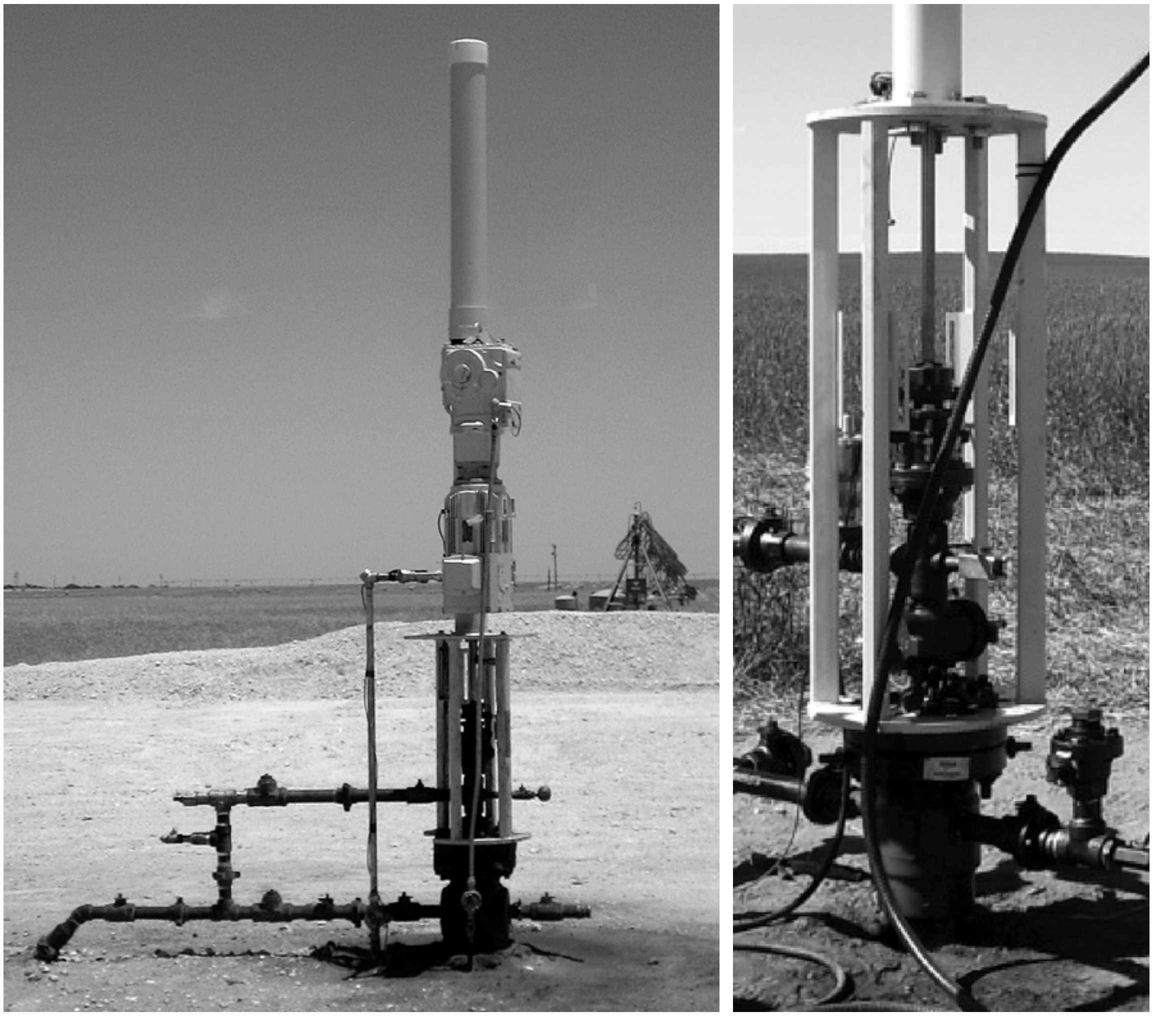


Figure 7—Linear Rod Pumping Casing Mounts

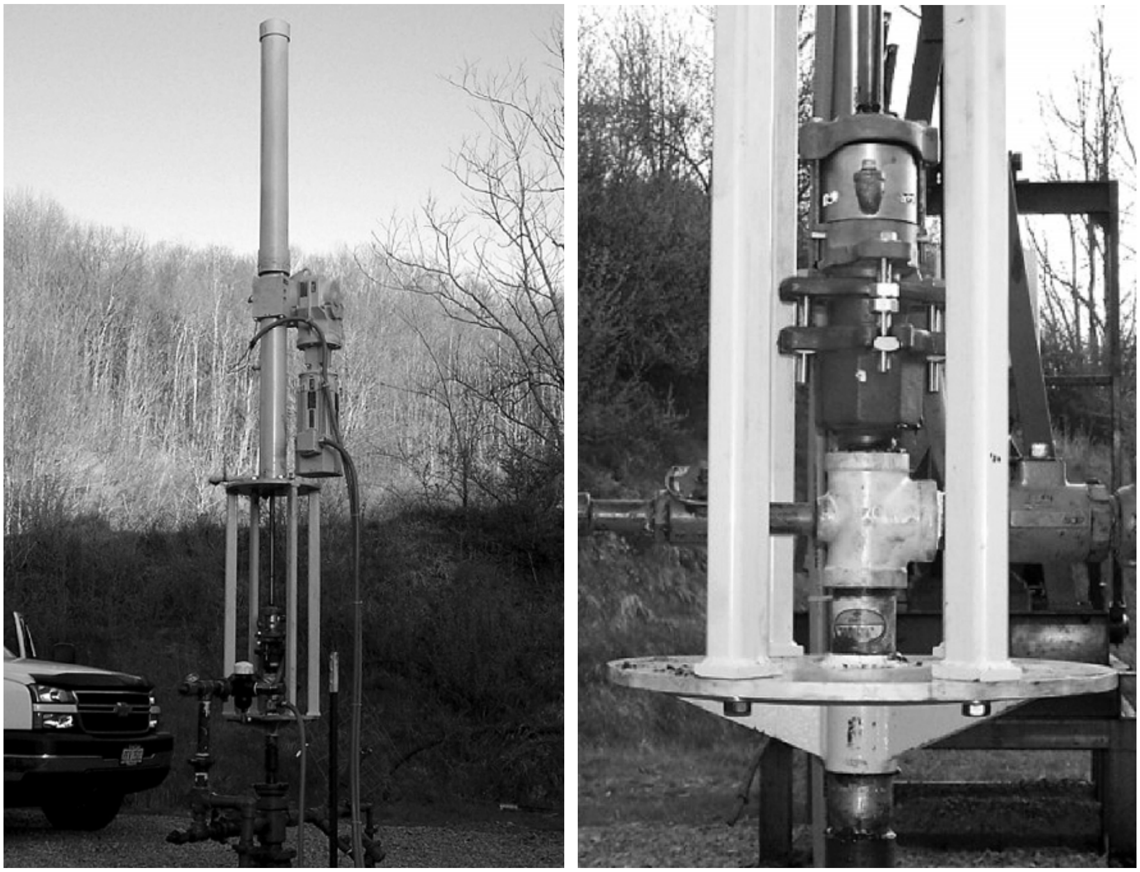


Figure 8— Linear Rod Pump Tubing Mounts

Figure 9— Progressing Cavity Pump Tubing Mount

Figure 10— Texas Linear Rod Pump Installation

Figure 11—New Mexico Linear Rod Pump Installation

Figure 12—Venezuela Linear Rod Pump Installation

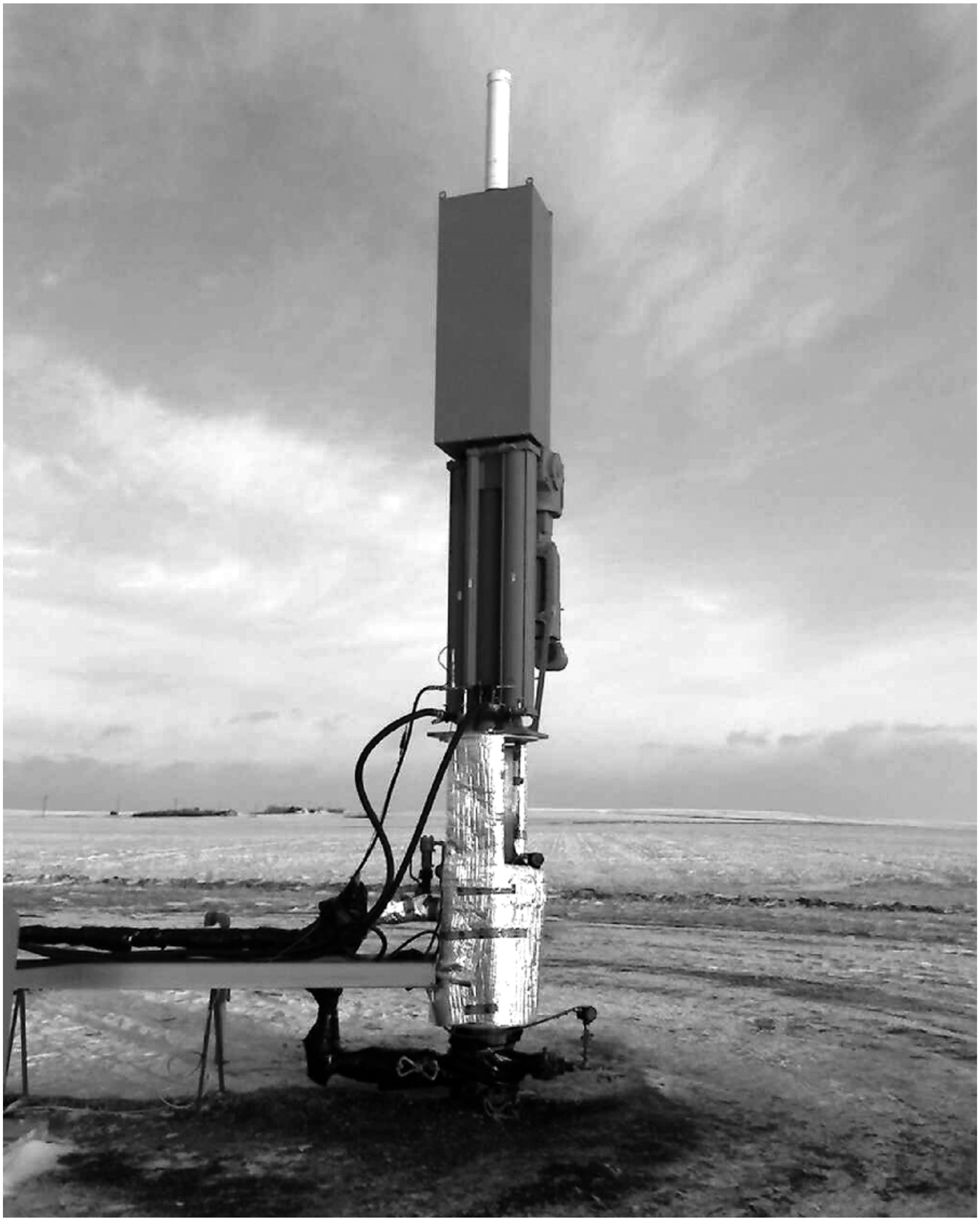


Figure 13—Air-Balanced Linear Rod Pump Installation

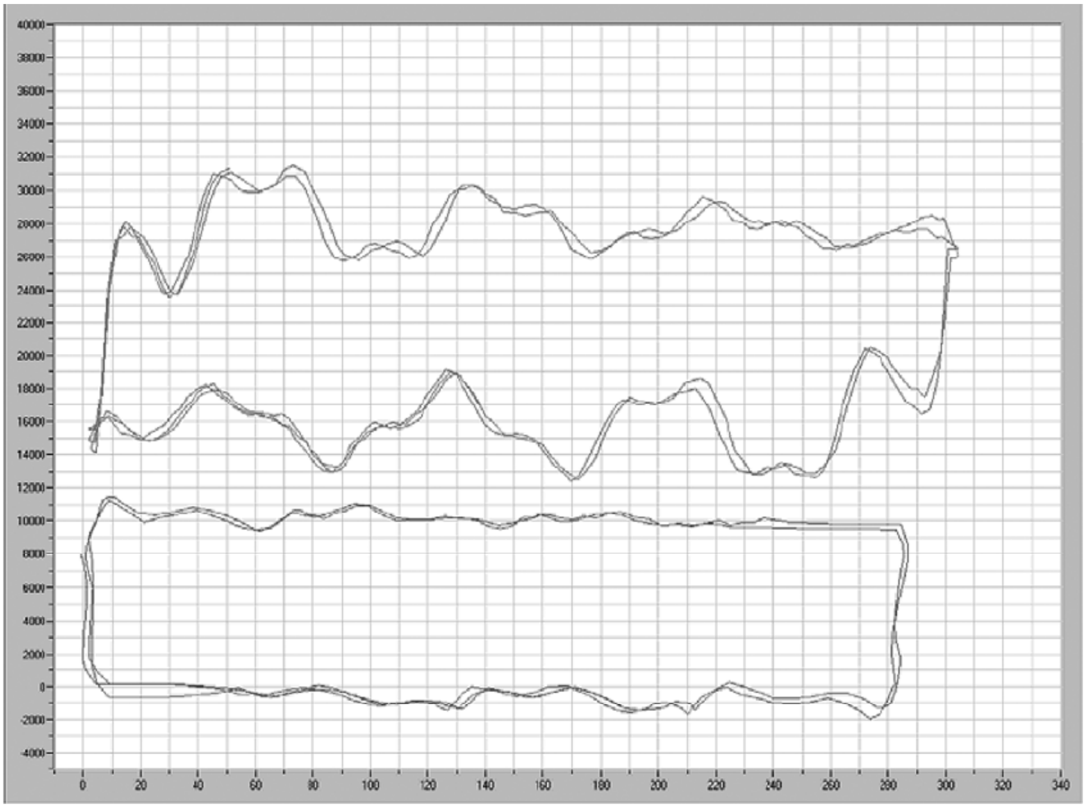


Figure 14—Measured Rotaflex® Dynamometer Cards

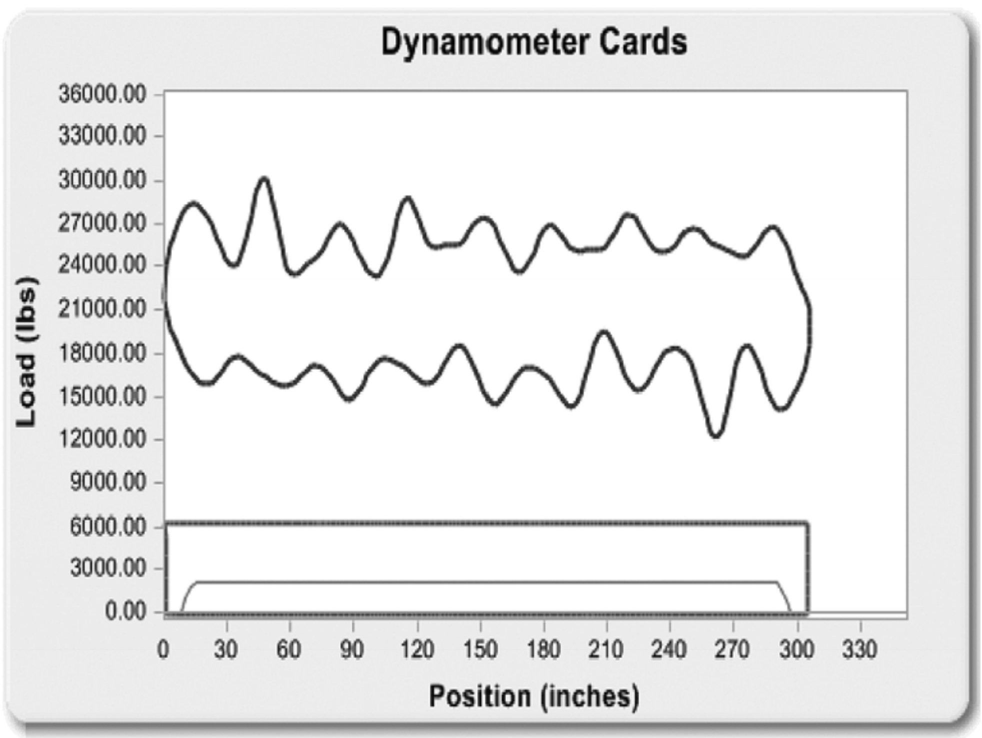


Figure 15—Simulated Rotaflex® Dynamometer Cards

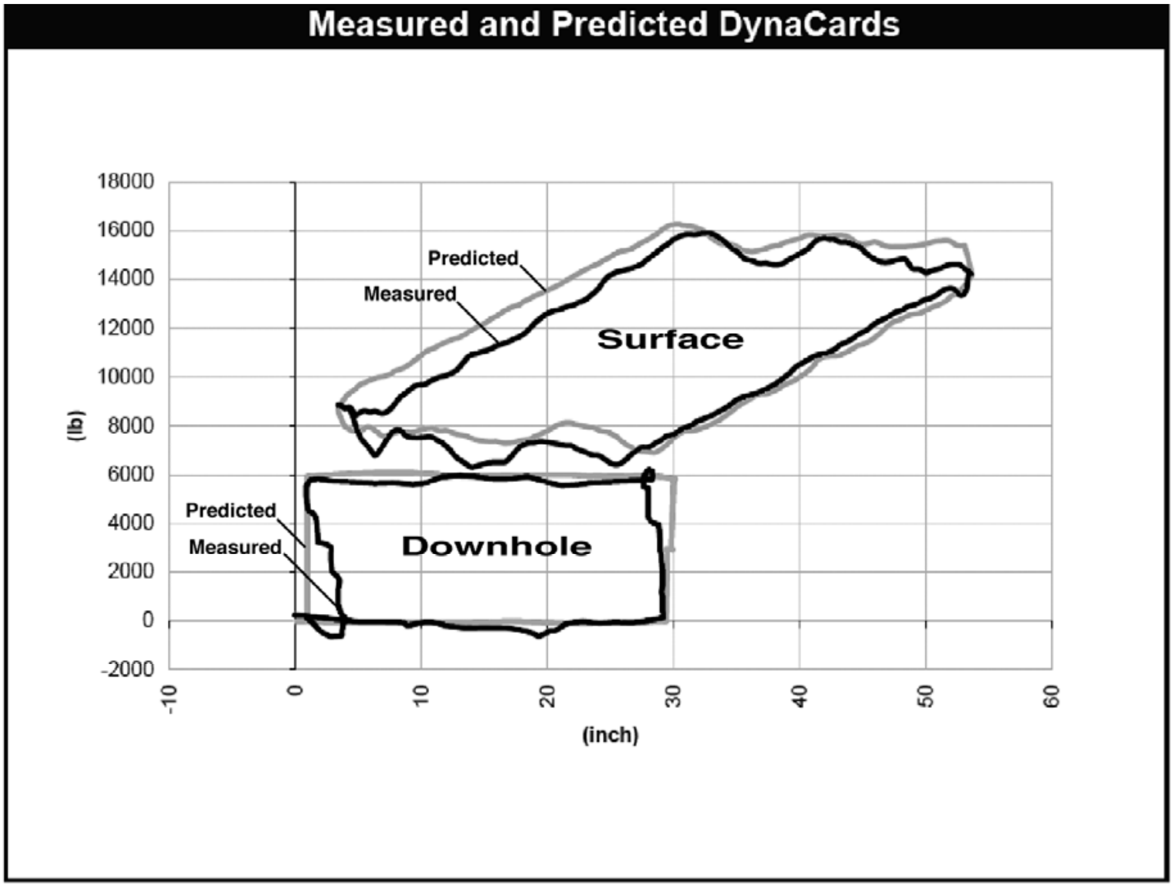


Figure 16—Linear Rod Pump Measured and Simulated Results

Pumping Unit Parameters	Code	Value
Pump (Con=C, Air=A, MII=M)	Pp	C
Pump Direction (cw or ccw)	Pq	cw
Rod/Pivot Distance (Inches)	Au	129.00
Equal/Pivot Distance (Inches)	Cu	111.07
Pivot Point Height (Inches)	Hu	232.00
Crankshaft Location (Inches)	Iu	111.00
Crankshaft Height (Inches)	Gu	96.00
Crankpin Radius (Inches)	Ru	42.00
Pitman Arm Length (Inches)	Pu	132.00
Phase Angle (Degrees)	Ao	0.00

System Input Parameters	Code	Value
Pump Depth (Feet)	Xp	5,000
Fluid Level (Feet)	Xf	5,000
Tubing Anchor (Feet)	Xt	0
Upper Rod Diameter (Inches)	Du	0.875
Lower Rod Diameter (Inches)	Dl	0.750
Upper Rod Fraction (%)	Fa	33.8%
Lower Rod Fraction (%)	Fb	66.2%
Plunger Diameter (Inches)	Dp	1.500
Tubing Diameter (Inches)	Dt	2.375
Rod Friction (Pounds)	Fr	100
Pump Friction (Pounds)	Fp	100
Pump Efficiency (%)	Ep	90%
Water Cut	Rw	90%
Water Specific Gravity	Gw	1.000
API Oil Grade	Ga	30.0
Tubing Pressure (Psi)	Pt	20
Casing Pressure (Psi)	Pc	10
SRP Pump Speed (Spm)	Nx	10.00
LRP Accel Time Ratio (%)	Ra	25%

Calculated Parameters	Code	Value
Fluid Specific Gravity	Gf	0.988
Rod String Load (Pounds)	Fs	7,969
Fluid Column Load (Pounds)	Fo	3,796
Optimum Counterbalance	Fe	9,917
Up Stroke Force (Pounds)	Fu	12,015
Down Stroke Force (Pounds)	Fd	7,819
Average Lift Power (Hp)	Pl	7.826
Polished Rod Power (Hp)	Pb	10.672
Rod Stretch Ratio	Rs	0.148
Oscillation Ratio	Rn	0.188
Oscillation Frequency (Spm)	No	53.250
Fall Velocity Speed (Spm)	Nf	18.468
Up Peak Speed (In/Sec)	Vu	54.213
Down Peak Speed (In/Sec)	Vd	53.791
Rod Stroke (Inches)	Sr	100.711
Fluid Load Stretch (Inches)	So	14.933
Friction Stretch (Inches)	Sf	0.393
Tubing Stretch (Inches)	St	6.021
SRP Pump Speed (Spm)	Np	10.000
SRP Pump Stroke (Inches)	Sp	96.442
SRP Pump Flow (Bpd)	Qp	212.516
LRP Pump Speed (Spm)	Npe	14.075
LRP Pump Stroke (Inches)	Spe	99.414
LRP Pump Flow (Bpd)	Qpe	308.997

Figure 17—Class I Geometry Pump versus Linear Rod Pump Parameters

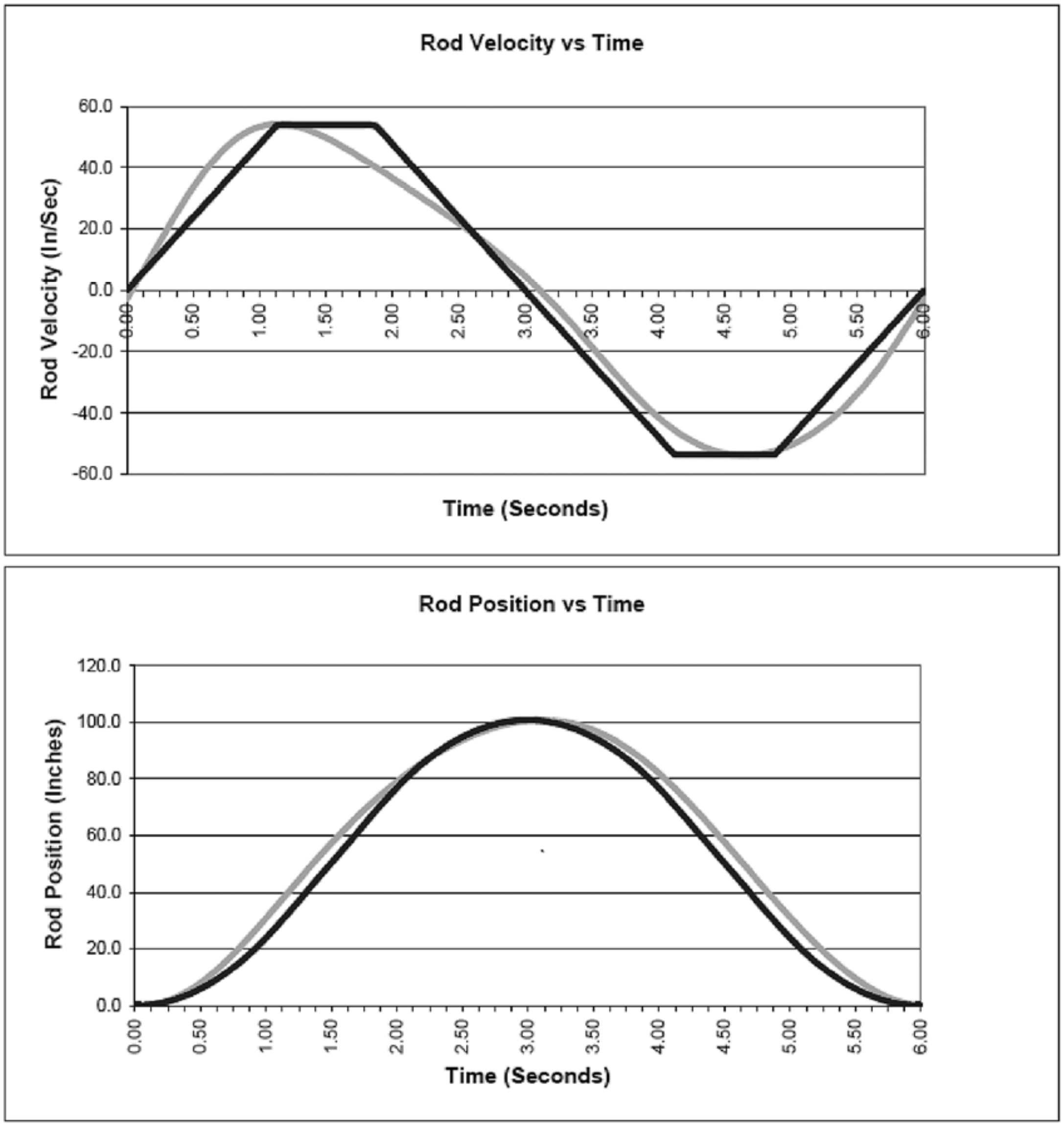
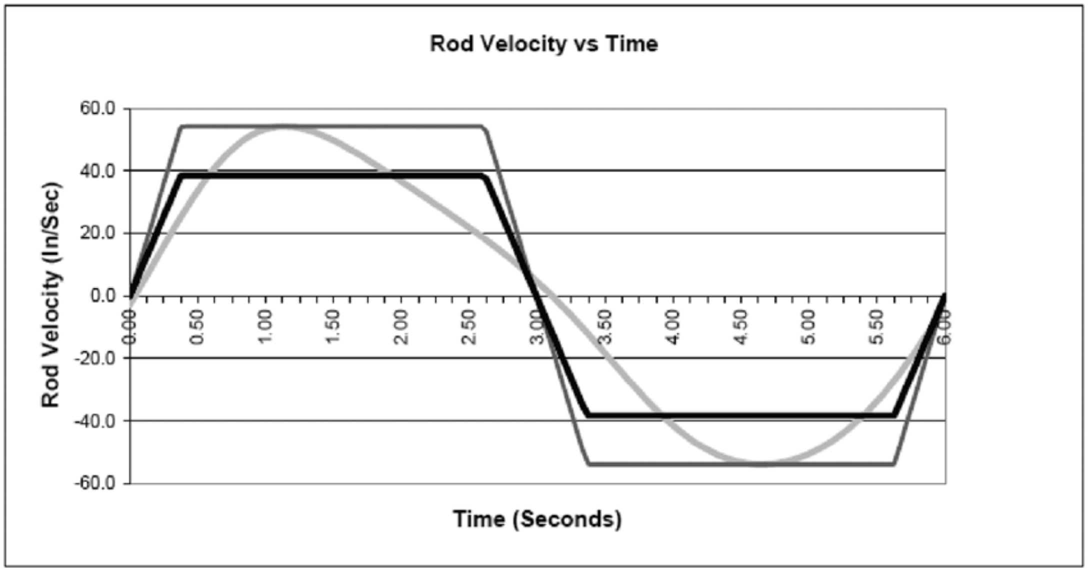


Chart Legend
Vra=SRP Rod Velocity
Vrc=LRP Rod Velocity (Stroke)
Xra=SRP Rod Position
Xrc=LRP Rod Position (Stroke)

Performance Comparison	SRP	LRP	Ratio
Pump Speed (Spm)	10.00	10.05	100.5%
Pump Stroke (Inches)	96.44	96.52	100.1%
Pump Flow (Bpd)	212.5	213.8	100.6%

Figure 18—Class I Geometry Pump versus LRP with 75% Acceleration Time



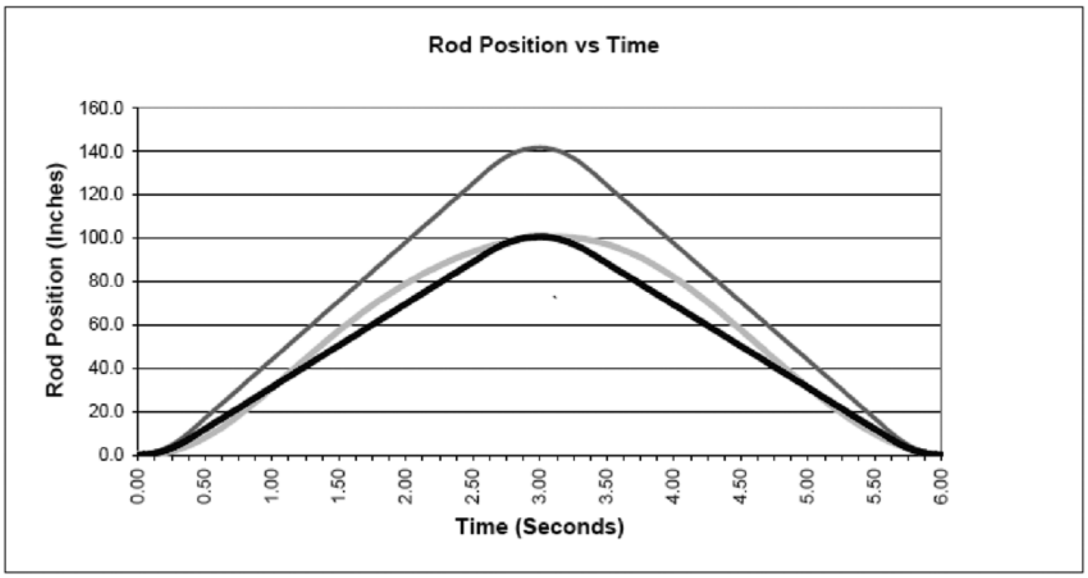


Chart Legend
Vra=SRP Rod Velocity
Vrb=LRP Rod Velocity (Velocity)
Vrc=LRP Rod Velocity (Stroke)
Xra=SRP Rod Position
Xrb=LRP Rod Position (Velocity)
Xrc=LRP Rod Position (Stroke)

Performance Comparison	SRP	LRP	Ratio
Pump Speed (Spm)	10.00	14.08	140.8%
Pump Stroke (Inches)	96.44	99.41	103.1%
Pump Flow (Bpd)	212.5	309.0	145.4%

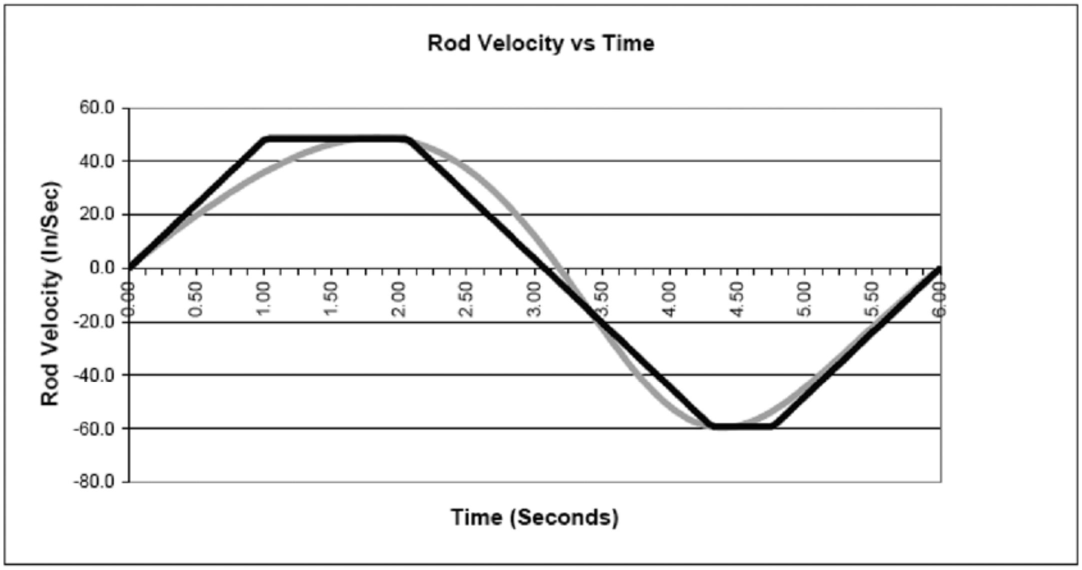
Figure 19—Class I Geometry Pump versus LRP with 25% Acceleration Time

Pumping Unit Parameters	Code	Value
Pump (Con=C, Air=A, MII=M)	Pp	M
Pump Direction (cw or ccw)	Pq	ccw
Rod/Pivot Distance (Inches)	Au	312.00
Equal/Pivot Distance (Inches)	Cu	258.00
Pivot Point Height (Inches)	Hu	277.13
Crankshaft Location (Inches)	Iu	186.00
Crankshaft Height (Inches)	Gu	118.13
Crankpin Radius (Inches)	Ru	37.63
Pitman Arm Length (Inches)	Pu	173.75
Phase Angle (Degrees)	Ao	30.00

System Input Parameters	Code	Value
Pump Depth (Feet)	Xp	5,000
Fluid Level (Feet)	Xf	5,000
Tubing Anchor (Feet)	Xt	0
Upper Rod Diameter (Inches)	Du	0.875
Lower Rod Diameter (Inches)	Dl	0.750
Upper Rod Fraction (%)	Fa	33.8%
Lower Rod Fraction (%)	Fb	66.2%
Plunger Diameter (Inches)	Dp	1.500
Tubing Diameter (Inches)	Dt	2.375
Rod Friction (Pounds)	Fr	100
Pump Friction (Pounds)	Fp	100
Pump Efficiency (%)	Ep	90%
Water Cut	Rw	90%
Water Specific Gravity	Gw	1.000
API Oil Grade	Ga	30.0
Tubing Pressure (Psi)	Pt	20
Casing Pressure (Psi)	Pc	10
SRP Pump Speed (Spm)	Nx	10.00
LRP Accel Time Ratio (%)	Ra	25%

Calculated Parameters	Code	Value
Fluid Specific Gravity	Gf	0.988
Rod String Load (Pounds)	Fs	7,969
Fluid Column Load (Pounds)	Fo	3,796
Optimum Counterbalance	Fe	9,917
Up Stroke Force (Pounds)	Fu	12,015
Down Stroke Force (Pounds)	Fd	7,819
Average Lift Power (Hp)	Pl	7.759
Polished Rod Power (Hp)	Pb	10.598
Rod Stretch Ratio	Rs	0.149
Oscillation Ratio	Rn	0.188
Oscillation Frequency (Spm)	No	53.250
Fall Velocity Speed (Spm)	Nf	14.487
Up Peak Speed (In/Sec)	Vu	48.816
Down Peak Speed (In/Sec)	Vd	59.579
Rod Stroke (Inches)	Sr	100.012
Fluid Load Stretch (Inches)	So	14.933
Friction Stretch (Inches)	Sf	0.393
Tubing Stretch (Inches)	St	6.021
SRP Pump Speed (Spm)	Np	10.000
SRP Pump Stroke (Inches)	Sp	95.668
SRP Pump Flow (Bpd)	Qp	210.687
LRP Pump Speed (Spm)	Npe	14.085
LRP Pump Stroke (Inches)	Spe	98.599
LRP Pump Flow (Bpd)	Qpe	306.496

Figure 20—Class III Geometry Pump versus Linear Rod Pump Parameters



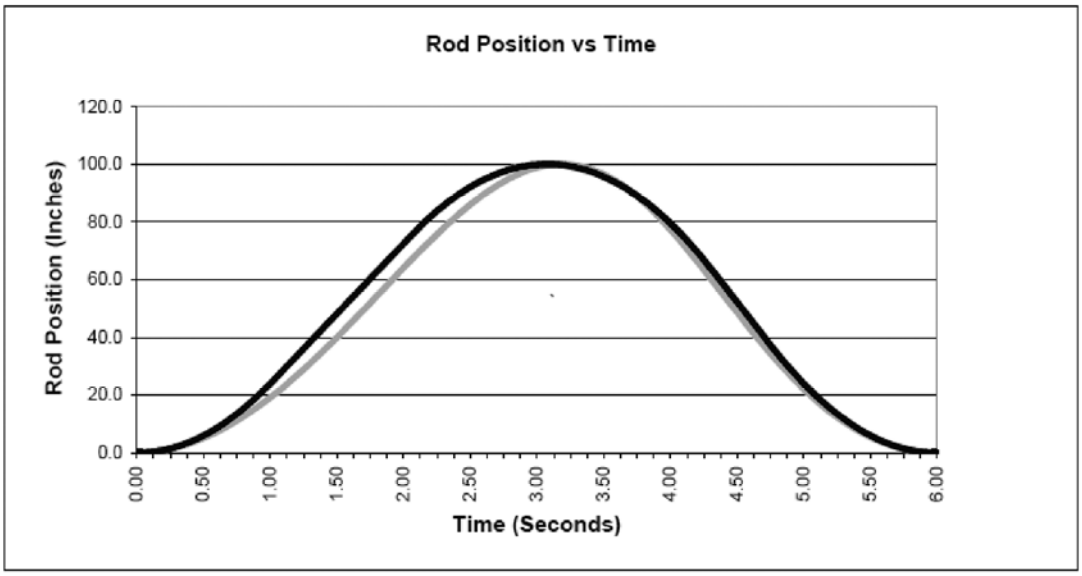


Chart Legend
Vra=SRP Rod Velocity
Vrc=LRP Rod Velocity (Stroke)
Xra=SRP Rod Position
Xrc=LRP Rod Position (Stroke)

Performance Comparison	SRP	LRP	Ratio
Pump Speed (Spm)	10.00	10.06	100.6%
Pump Stroke (Inches)	95.67	95.75	100.1%
Pump Flow (Bpd)	210.7	212.2	100.7%

Figure 21—Class III Geometry Pump versus LRP with 75% Acceleration Time

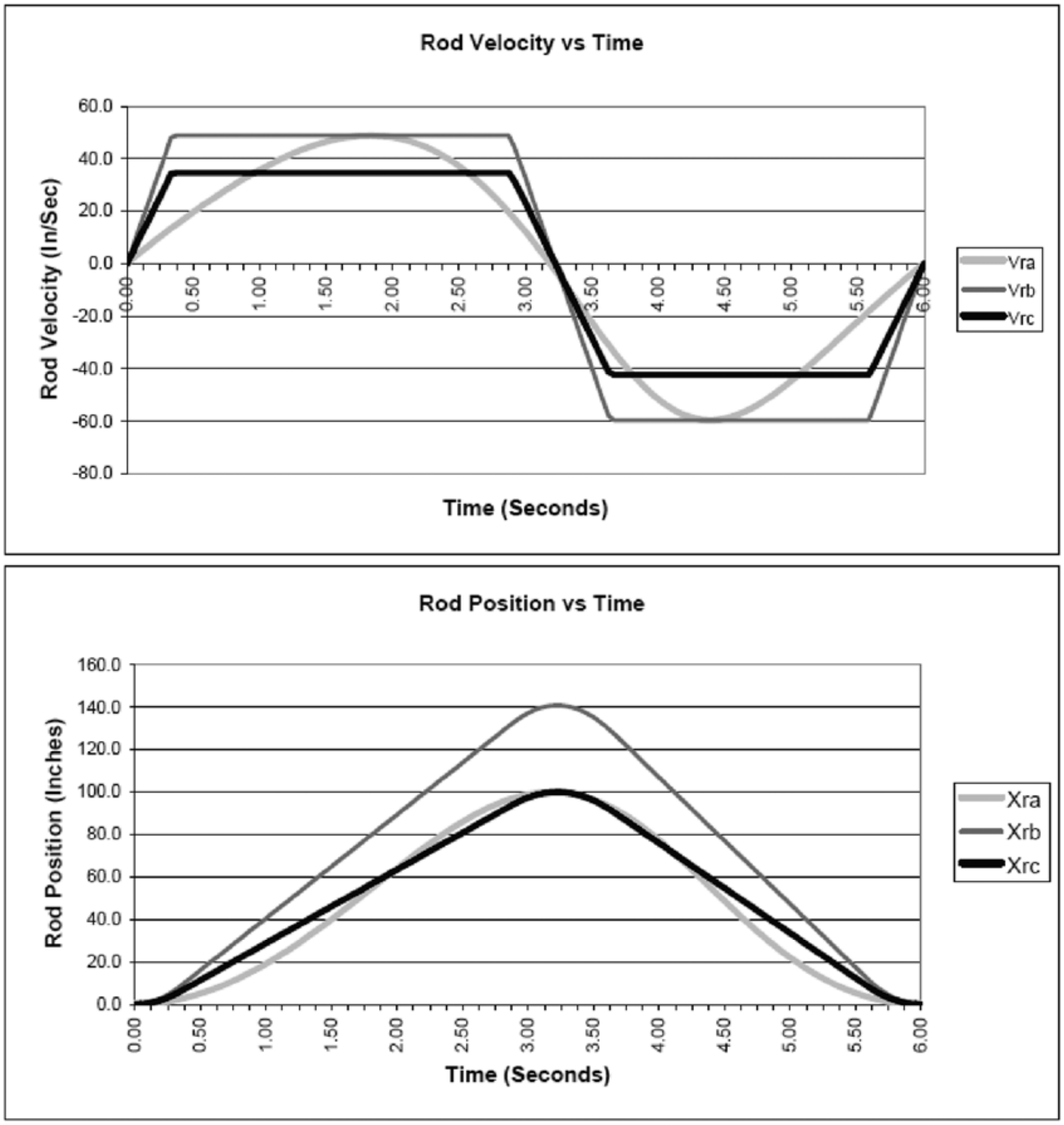


Chart Legend
Vra=SRP Rod Velocity
Vrb=LRP Rod Velocity (Velocity)
Vrc=LRP Rod Velocity (Stroke)
Xra=SRP Rod Position
Xrb=LRP Rod Position (Velocity)
Xrc=LRP Rod Position (Stroke)

Performance Comparison	SRP	LRP	Ratio
Pump Speed (Spm)	10.00	14.08	140.8%
Pump Stroke (Inches)	95.67	98.60	103.1%
Pump Flow (Bpd)	210.7	306.5	145.5%

Figure 22—Class III Geometry Pump versus LRP with 25% Acceleration Time

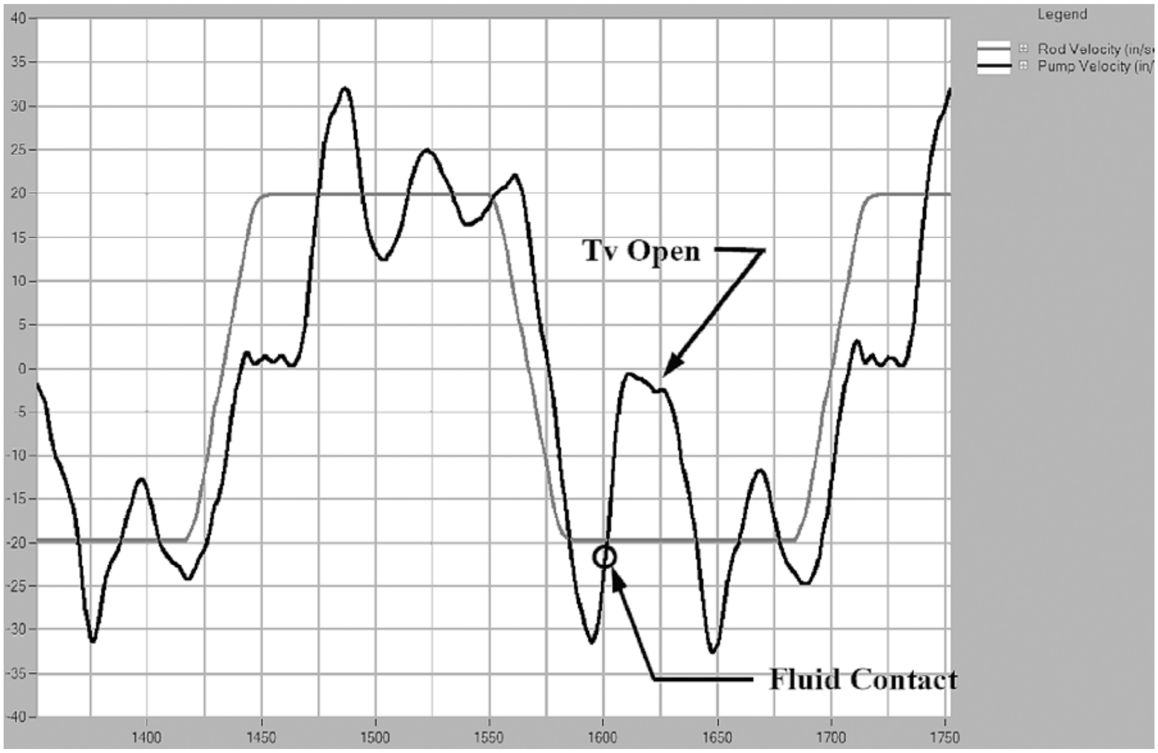


Figure 23—Rod and Plunger Velocity for Fixed Velocity Profile

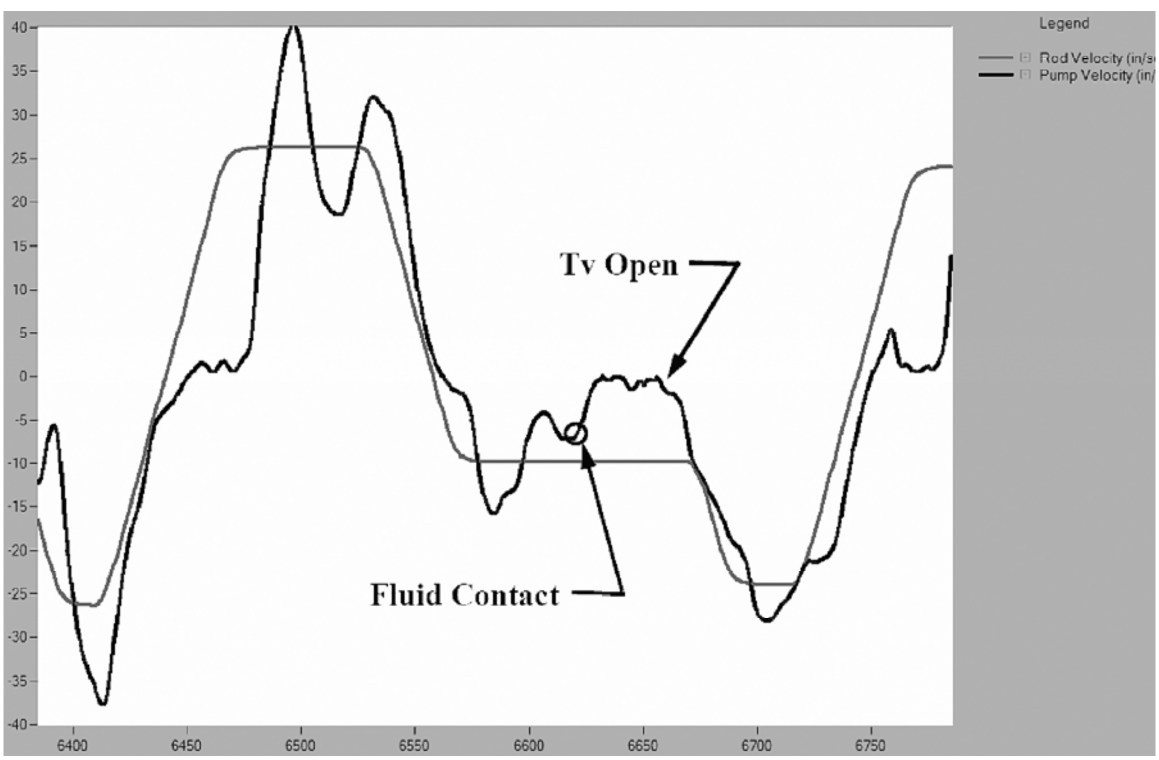


Figure 24—Rod and Plunger Velocity for Soft Landing Profile

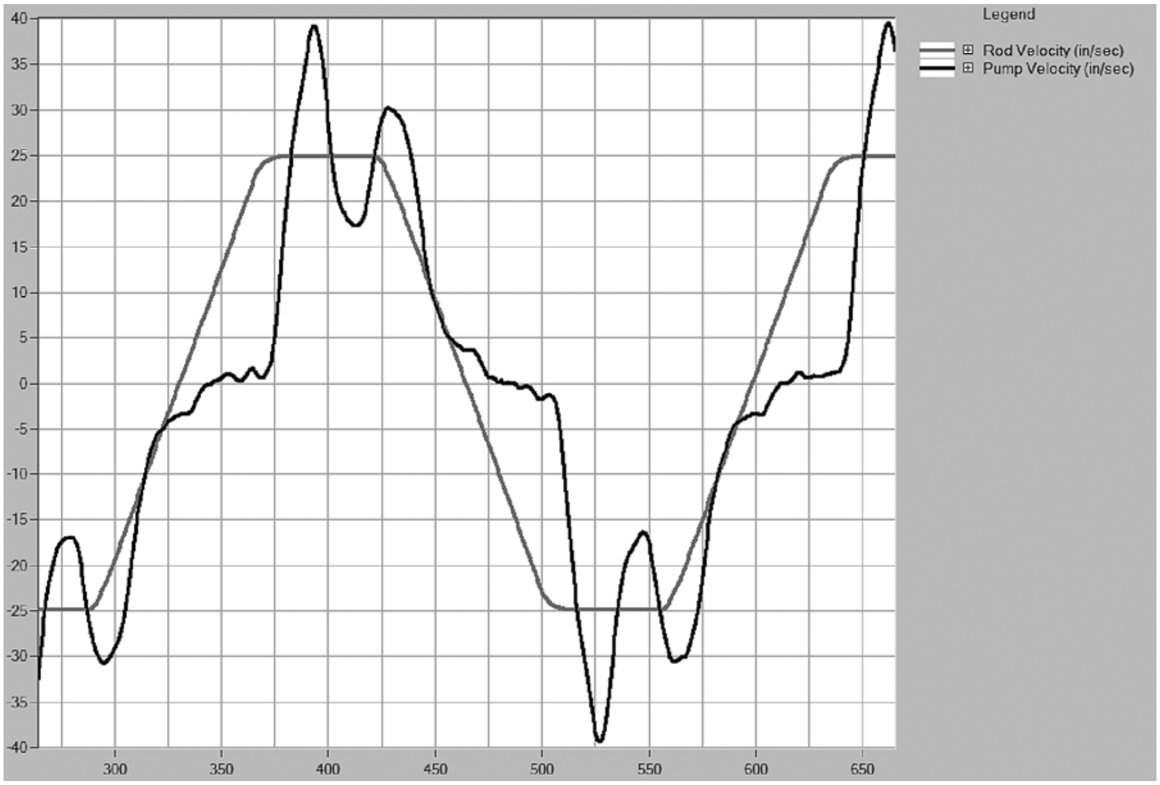


Figure 25—Rod and Pump Velocity for Fixed Velocity Profile

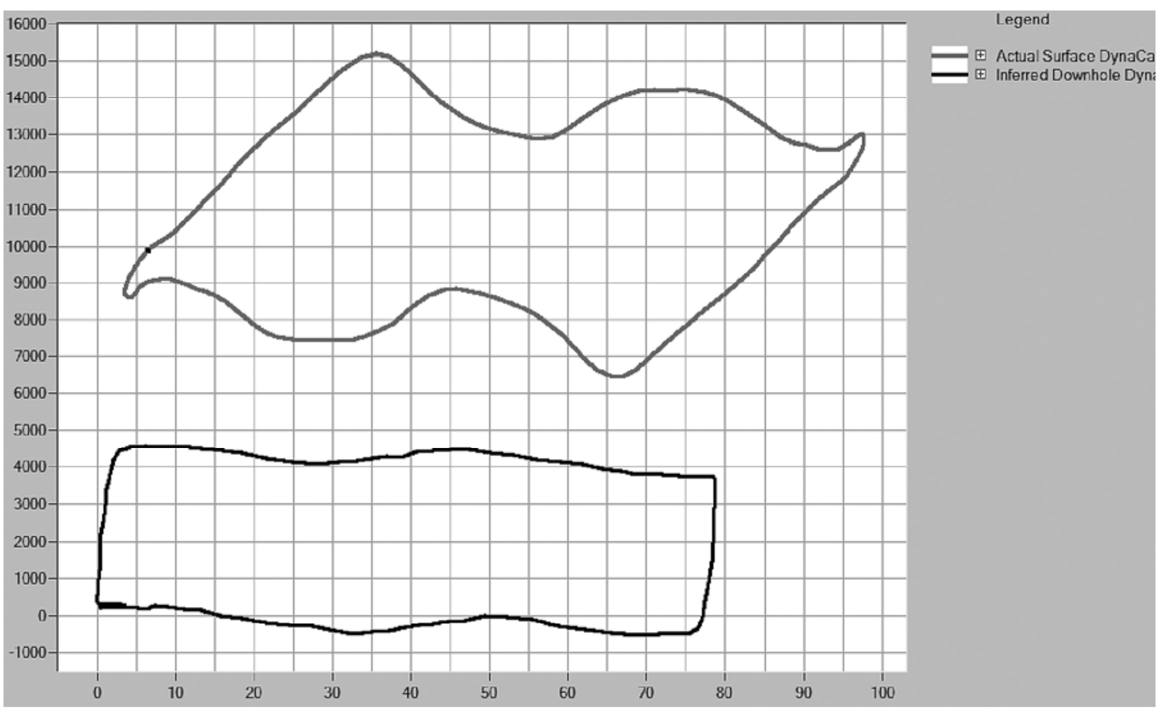


Figure 26—Rod and Pump Dynamometer Card for Fixed Velocity Profile

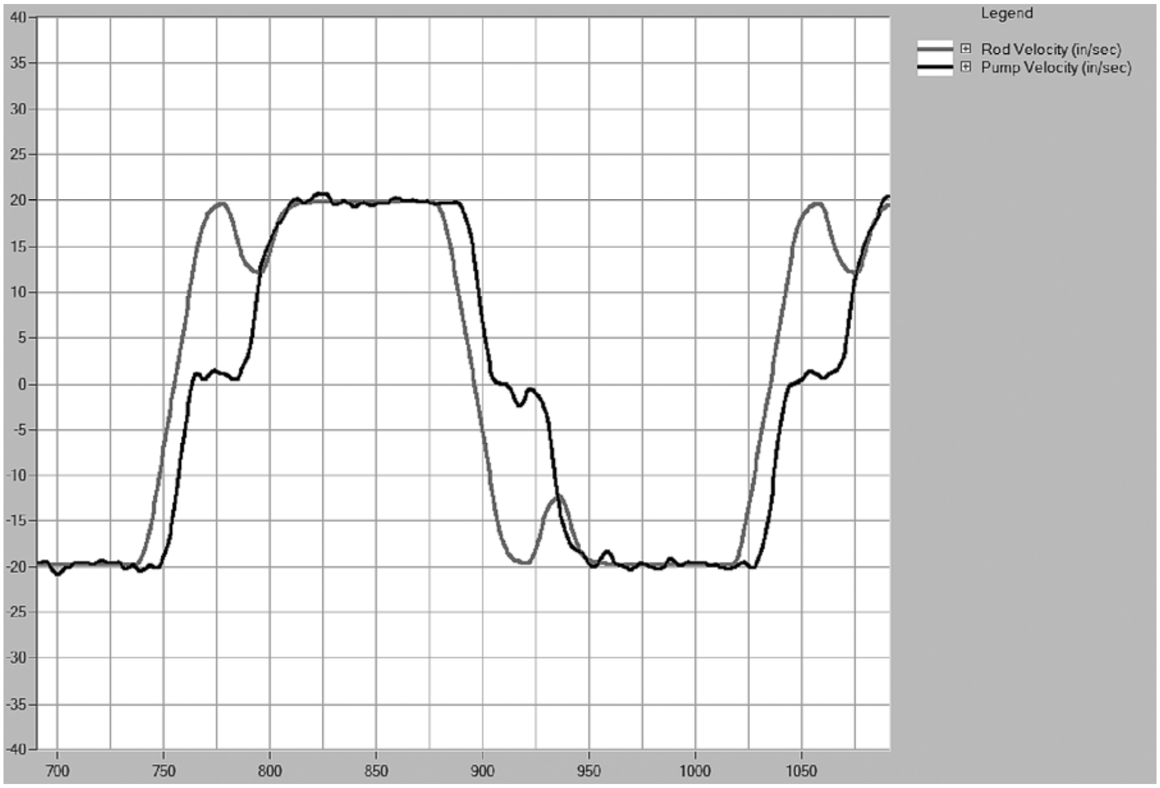


Figure 27—Rod and Pump Velocity for Closed Loop Control

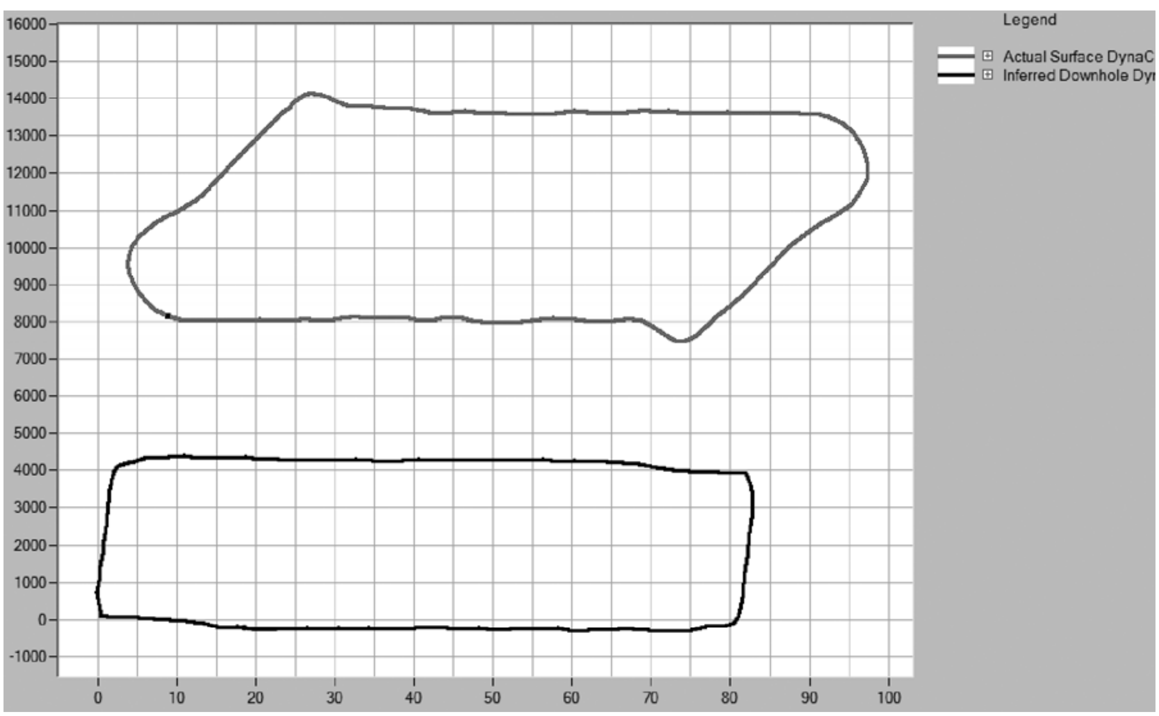


Figure 28—Rod and Pump Dynamometer Cards for Closed Loop Control