Progress Report #3 on "Fluid Slippage in Down-Hole Rod-Drawn Oil Well Pumps"

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Abstract and Scope

This paper will present results of two field slippage tests and compare these results with laboratory testing of pump slippage presented in the 1998 Southwestern Petroleum Short Course paper and field application of larger clearance pumps. This is Progress Report **#3,** with the ultimate goal being to present an empirical equation which will estimate the down-hole fluid slippage over a wide range of pump clearances. Utilizing the field test data an empirical equation is presented. The current results should be useful to operators for selection of clearances between metal plungers and barrels.

Summary of Results

Most fluid slippage equations have overstated the slippage of down-hole, rod-drawn positive displacement pumps with metal plungers. The historical equations predict about twice the observed slippage for clearances equal to or less than .006" (six thousandths of an inch) depending on the historical equation. For clearances larger than .006" these historical equations can overestimate the slippage by a factor greater than three. However, the Robinson-Reekstin empirical equation approximated the lab data below a clearance of 0.010".

Based on field testing, the Robinson-Reekstin equation under predicts but provides reasonable results up to a clearance of 0.008" to 0.010". Above 0.010", the Robinson-Reekstin equation over predicts fluid slippage as confirmed by both lab and field test data. Both field tests well were able to produce fluid. although at a reduced volumetric efficiency, at pump clearances when the Robinson-Reekstin equation predicted that the fluid slippage would be in excess of the pump capacity.

The fluid slippage, for different clearances using a 1.75" pump, measured in the field tests using water has provided a new empirical equation, the ARCO-HF equation, which more closely matches the actual slippage from the field tests over a wide range of clearances.

$$\text{Slippage in BPD} = 870 \frac{D P C^{1.52}}{L \mu} \qquad \text{ARCO-HF Equation, based on Field Tests}$$

where: 870 is an empirical and dimensional constant
D = plunger diameter in inches
C = clearance between plunger and barrel in inches, with an exponent of 1.52
L = plunger length in inches
μ = viscosity in centipoise
P = differential pressure across the plunger in psi

Field application of larger clearance pumps in SE New Mexico have verified that larger clearance pumps (0.007" to 0.012") will produce at high pump efficiencies even at high water cuts. The high efficiencies with larger clearance pumps emphasize the impact of the in-situ viscosity on reducing pump slippage.

History

Oil well owners and operators have always been sensitive to the amount of fluid slippage past a metal plunger during operation of a rod-drawn, down-hole pump. This slippage of fluid lowers pumping efficiency by leaking high-pressure fluid past the plunger back into the pump compression chamber. The minimum amount of fluid slippage is recommended to be about two percent of the produced fluid. This equates to a pump clearance of typically 0.002" to 0.004". Historically a pump has been considered worn out when the plunger and/or barrel wears to a point that the fluid slippage affects daily fluid production.

Slippage past a metal plunger is necessary for lubrication. The metal plunger needs a film of fluid between **it** and the metal barrel to prevent galling. Also pump clearance is necessary to allow particulates to pass between the plunger and the barrel without the plunger becoming stuck. Secondly, increased clearances will reduce pump drag and reduce sticking due to solids. However, there is a limit to the clearance that can be used while maintaining reasonable fluid slippage.

Historical equations [1,2,3,4,5,6,7] have taken the general form of the equation listed below with slight differences in the leading constant (K) and/or exponents on the variables in the equation. *It should be noted that all of the following discussions on the various leakage equations are based upon a constant differential pressure being applied across the plunger. In an oil well installation, the differential pressure is only applied during half of the cycle (upstroke); therefore, the leakage equations should be divided by two. The authors will point out when the equations, being divided by 2, reflect downhole conditions.* There have been several efforts to measure the fluid slippage and develop empirical equations to match the measured data. **A** listing of these equations can be found in interim report number 1.

$$\text{Slippage in BPD} = K \, \frac{D^a \, P \, C^b}{L \, V}$$

where: K = constant
D = plunger diameter in inches, with exponent a which varies from *0.7* to 1.0
C = clearance between plunger and barrel in inches, with an exponent b which varies from *3.0* to *3.3*
L = plunger length in inches
V = viscosity in centipoise
P = differential pressure across the plunger in psi

As reported in interim Report #1, Reekstin evaluated data presented by Robinson[6] who did a test in a well at 4000' with out a standing valve. Static pressure was determined by two subsurface pressure surveys. The tubing was filled with oil from the surface and the pump was operated using the existing pumping unit at a constant speed. Leakage past the plunger was determined by gauging the amount of oil (*33.5* API) necessary to keep the tubing full. A 1.5" plunger 72" long was used in the test. Reekstin used the graph presented by Robertson and developed the following equation:

$$\text{Slippage in BPD} = 5.6 \times 10^6 \; \frac{D^{0.7}\, P\, C^{3.3}}{L\, \mu} \qquad \text{Robinson-Reekstin}$$

Correcting the constant for the pumping cycle yields the following

$$\text{Slippage in BPD} = 2.8 \times 10^6 \; \frac{D^{0.7}\, P\, C^{3.3}}{L\, \mu} \qquad \text{Robinson-Reekstin}$$

where: 5.6×10^6 is the empirical and dimensional constant with a constant differential pressure
2.8×10^6 is the empirical and dimensional constant which has been divided by two to represent the differential pressure is applied only on the up stroke.
D = plunger diameter in inches, with an exponent of 0.7
C = clearance between plunger and barrel in inches, with an exponent of ***3.3***
L = plunger length in inches
μ = viscosity in centipoise
P = differential pressure across the plunger in psi

Since the Robinson-Reekstin equation provided the best fit of the measured data, up to a clearance of 0.008" to 0.010", this equation has been used for comparison to the lab and field slippage measured data.

It should be noted that the Robinson-Reekstin equation was derived under pumping conditions using oil and the new equation circulated water to measure the fluid slippage.

Field Test Setup and Analysis

Table 1 Test Equipment

Two field tests were conducted to measure fluid slippage. Wells that were temporarily abandoned were utilized to measure the fluid slippage using a 1.75" pump with different clearances. Table 1 summarizes the equipment used in both field tests. The pumping installation was held reasonably constant using a 456 MarkII pumping unit, a 1" rod string, 2-7/8" tubing, 144" stroke and 6.6 SPM. The differences between the first and second field test were the fluid quality (fresh water unfiltered vs. filtered), pump setting depth (2520 vs. 4994), tubing anchor (unanchored vs. anchored), tubing pressure (variable vs. fixed), plunger length (50" vs. 38") and pump clearances (four from 0.0052" to 0.0166" vs. six from 0.0037" to 0.0209").

By minimizing the pump system variables the impact of pump clearance on fluid slippage, power, rod loads and pump drag could be isolated.

Field Test #1 [12] - **A** test pump was inserted and the well was pumped through a positive displacement meter and a backpressure valve with the fluid returned to the tubing/casing annulus. The back-pressure valve was used to create three different pressure cases to artificially increase the differential pressure across the plunger simulating different pump depths. Each pump was tested at different back-pressures. Cumulative pumped volumes were recorded, during a 30 to 50 minute period, for each pump at each pressure setting. After stabilized data was obtained, a different clearance pump was installed and tested.

After review of the information and data from the first field test presented in Progress Report #2, concern was expressed on the use of back pressure to simulate depth, the effect of erratic valve action and trash, and the use of a single surface meter. Field Test #2 was designed to eliminate these issues identified with the first field test.

Field Test #2 – **A** deeper well with anchored tubing was utilized in the second field test and only one set on data was obtained with each pump as minimum back pressure was used in the second field test. Dual surface meters and filters were utilized to reduced problems associated with “trash” in the well. Other than these differences, the general test procedure was the same for both field tests. Tests pumps included both smaller and larger clearances than were used in the first field test.

The PD meters were proved after the test and found to be accurate

Field Test Fluid Slippage

Table 2	Fluid Slippage and Pump Efficiency
Figure 1	Surface measured rate versus pump clearance for Field Tests #1 and #2
Figure 2	Pump Efficiency versus Pump Clearance **for** Field Tests #1 and #2
Figure **3**	Net Pump Stroke Length versus Pump Clearance for Field Tests #1 and #2
Figure 4	Fluid slippage versus Pump Clearance for Field Test #1 – High Pressure Case
Figure 5	Fluid slippage versus Pump Clearance for Field Test #2.
Figure ***6***	Fluid slippage versus Pump Clearance for Combining Field Tests #1 and #2
Figure 7	Curve fit of normalized field data
Figure **8**	Comparison of Fluid slippage versus Pump Clearance for Field Tests and Lab Data.
Figure 9	Field empirical equation compared to field data
Figure 10	Lab data normalized to Field Test #2 conditions

Fluid slippage was calculated by three different methods. Test data and calculated values are presented in Table 2 and graphically for both field tests in Figure 1. The three methods used to determine fluid slippage are defined as follows:

Method 1 - Using a surface load cell, a downhole dynamometer card was calculated to determine the net stroke length. The net stroke length was used to calculate the pump displacement. Subtracting the surface metered rate from the net pump displacement in BPD, yields the fluid slippage.

Method 2 - Valve stops were made and the Nabla rate of change of the traveling valve load was used to calculate the fluid slippage.

Method 3 - The Robinson-Reekstin equation was used with the test parameters to calculate the fluid slippage using the average tubing pressure and the calculate the plunger differential pressure.

Pump clearance – shop measured versus calculated downhole - Shop clearance was used as the basis of evaluation and presentation as opposed to a calculated downhole clearance for each pump. After each test, the pump was torn down and the ID of the barrel and the OD of the plunger were measured. An average value was determined for each component and the shop diametric clearance was used in the analysis. The change in downhole clearance was calculated for the 1.75” RHBC barrel, using the calculated differential pressure between the pump discharge to pump suction pressure, was between -

0.00143" to -0.00149". However, the pressure distribution across the plunger is zero at the top of the plunger and maximum at the bottom of the plunger. **If a** linear pressure distribution is assumed then only half of the pressure differential is used to calculate slippage resulting in the change in barrel ID to be between –0.00072" and –0.00074". Since it is not totally understood how the barrel wall thickness changes with pressure across the plunger and that these changes were small, the shop clearances were used in the evaluation.

Method 1 - The only dynamic method uses the fluid displacement based on the net downhole stroke minus the surface meter reading (Method 1). Table 2 lists the calculated fluid slippage using the Robinson-Reekstin equation, the calculated downhole stroke length, the net pump displacement and the calculated pump efficiency for each case. Figure 1 graphically compares the surface measured rate for different clearance pumps for both field tests. Figure **2** shows the pump efficiency for both field tests. Pump efficiency by definition is the ratio of the surface rate to the pump displacement. In each case the pump cards were full.

In the first field test increased tubing pressure was used to simulate a deeper well depth and the high pressure case in first field test should approximate the fluid load approximately similar to the second field test. Only the tests from the first field test, using pumps with the alternate pattern valves, which had full cards, were used in the comparisons to Field Test #2. The surface production was less in the second field test than the first but the plunger length was 50" in field test 1 as compared to 38" in Field Test #2. **A** similar difference is shown in the pump efficiencies plotted in Figure 2. There is a significant difference between the net stroke lengths in Field Test #1 and #2. Field Test #1 did not have anchored tubing as opposed to anchored tubing in the second field test. The tubing stretch in the first field test was 1.4" in the low pressure cases and increased to 2.8" in the high pressure cases. The net downhole stroke length is measured using the downhole card and in the first field test the net stroke length is reduced by the tubing stretch. In all cases as the net stroke increased with pump clearance. Clearly the pump slippage, defined as the difference between the pump displacement and surface production, is dynamic. If a constant net stroke length were used, the calculated slippage using method 1 would have been greater. Attempts were made to acquire the downhole dynamometer for the second field test were unsuccessful. To confirm some of these observations another field test using the downhole dynamometer at the pull rod of the pump would be necessary.

Method 2 - Nabla's method [13] of load change on the traveling valve is done during a traveling valve check with the plunger stationary. Valve stops were made with each pump clearance and each tubing pressure. Fluid slippage was calculated by Nabla using their rate of change of the traveling valve load and is shown in Table 2 and Figures 4 and 5. These slippage values, in Field Test #1, under-predicted the fluid slippage as measured during the test using Method 1 at all pump clearances. However, in Field Test #2 the Nabla TV slippage measurements under-predicted below a clearance of 0.010" and closely matched at 0.010" and higher clearances. The low values of the Nabla TV slippage measurements in Field Test #1 were due the test conditions and the use of pressure to simulate deeper pump setting depths. The higher pressure could not be maintained during the valve checks resulting in the lower calculated slippage value. The results in the second field test when compared to the measured slippage (Method 1) provide an indication that below a clearance of 0.010" that pump drag is interfering with the change of loads. Consider the table below with data from the second field test:

Test	Clearance	Slippage BPD Method 1	Slippage BPD Nabla	% change
1	0.0058"	26	17.5	-33%
2	0.0058"	46	21.0	-54%
3	0.0086"	80	58.1	-27%
4	0.0105"	109	120.0	+10%
5	0.0170"	183	177.0	-3.3%
6	0.0209"	245	253.0	+3.3%
7	0.0037"	20	5.6	-72%

Referring to the above table, the percent change of the Nabla slippage to Method 1 below 0.010" ranges from –74% (0.0037") to – 27% (0.0086"), but above 0.010" the pump drag is minimal allowing the change of load calculation to closely match the measured slippage (Method 1). Several observations indicate that the pump drag impacted the Nabla slippage below 0.010" and include the downhole card net stroke length and the residual friction (see section on system friction). With this collaboration, the difference in the Nabla leakage can be understood and also give confirmation of the fluid slippage by Method 1 at the higher clearances.

Method *3* – During the initial lab investigation of fluid slippage the Robinson-Reekstin Equation was found to be the published equation that most closely fit the lab data and became the equation used to compare the field results. The Robinson-Reekstin equation was used with the test parameters to calculate the fluid slippage using the average tubing pressure and the calculated the plunger differential pressure.

Based on the field testing (Table 2 and Figures 4 and 5), the Robinson-Reekstin equation under predicts but provides reasonable results up to a clearance of 0.008" to 0.010". Above 0.010", the Robinson-Reekstin equation significantly over predicts fluid slippage as confirmed by both lab and field test data. Both field tests were able to produce fluid, although at a reduced volumetric efficiency, at pump clearances when the Robinson-Reekstin equation predicted that the fluid slippage would be in excess of the pump capacity.

Field Test #2 validated the results from the first field test as shown by normalizing the data from the first field test to the conditions of the second field test using plunger length, differential pressure, and viscosity. See Figure 6.

Curve fitting of the lab and field data – Comparing the lab and field data to the Robinson-Reekstin Equation indicated that a new equation is required to represent a wider range of pump clearances that are being used in the industry. It should be noted that the clearances tested are beyond those tested in any of the previous tests found in the literature.

Figure 7 compares the fluid slippage measured in the lab and the field tests versus pump clearance. A curve was fitted through the data to show the relationship of fluid slippage to pump clearance for the data obtained in the lab versus the field. Figure 8 compares the data and fitted equation for lab and field data normalized to field test 2 conditions.

Using the field test data an empirical equation, the ARCO-HF equation, was derived as follows:

$$D\,P\,C^{1.52}$$

$$\text{Slippage in BPD} = 870 \; \frac{\qquad}{L\,\mu}$$

ARCO-HF Equation based on Field Tests

where: 870 is an empirical and dimensional constant
D = plunger diameter in inches, with an exponent of 1.0
C = clearance between plunger and barrel in inches, with an exponent of **1.5**
L = plunger length in inches
μ = viscosity in centipoise
P = differential pressure across the plunger in **psi**

Figure 9 shows the ARCO-HF equation compared to the normalized data as previously shown with Figure 6.

Measurement of static fluid slippage in the laboratory - The testing using a 1.75” pump was performed at EVI Oil Tools, Trico Industries, Inc. location, at San Marcos, Texas in the Hydraulic Test Lab. To maintain the desired rate and pressure at the larger clearances, the hydraulic test loop was utilized. Plungers were made to include clearances of 0.002”, 0.003”, 0.004”, 0.005”, 0.006”, 0.007”, 0.008”, 0.009”, 0.010”, 0.015” and 0.020”. All testing was done with the plunger and barrel in an upright position and the plungers were centralized using plunger centering fixtures. Barrels were suspended from the top so that slippage samples could be collected from the bottom of the test apparatus. The slippage sample was collected in a graduated container below the test apparatus. The temperature of the fluid as well as the viscosity was measured from this sample. The temperature of the fluid entering the top of the barrel was also measured and recorded. The fluid was a 10W (ten weight) hydraulic fluid with pressure and flow provided by an industrial triplex pump.

A curve fit through the lab data normalized to field test #2 conditions has the following form and is shown in Figure 10:

$$\text{Slippage in BPD} = \mathbf{6.95} \times 10^{4} \; \frac{D\,P\,C^{2.64}}{L\,\mu}$$

Lab data empirical equation

Note: Lab data was divided by two to account for the fact that, in a pumping cycle, differential pressure is only applied on the upstroke

Comparison of lab and field derived equations - There is a significant departure in the clearance exponent used in the empirical equations for the field test data and the lab data. The most significant difference is that the lab data was a static test (plunger velocity being zero) while the field tests were conducted as a dynamic test (actual pumping conditions). It should be noted that the largest clearance used in the lab data skews the curve fit; however, even if the high clearance lab data was discounted the lab data equation keeps approximately the same exponent **(2.77).**

Both the lab and field data depart from the Robinson-Reekstin equation at higher clearances. Obviously, more static testing in the lab is required at the larger clearances to understand the slippage at higher clearances. Hopefully additional lab testing will help understand the differences observed between the field and lab slippage with pump clearance. Lab testing provides a more cost effective method to confirm the slippage relationship under controlled conditions and allows for evaluating many different plunger sizes at different viscosities.

While the testing has focused on determining the impact of pump clearance on fluid slippage, several other factors were evaluated. They include the impact that pump clearance has on Minimum Polished Rod Load (MPRL), Peak Polished Rod Load (PPRL), and KWH used per barrel produced.

Rod Loads

Figure 11 Minimum Polished Rod Load versus pump clearance
Figure 12 Peak Polished Rod Load versus pump clearance
Figure 13 Comparison of Minimum and Peak Polished Rod Load versus pump clearance

Minimum Polished Rod Loads - **As** the pump clearance increases, one might expect that the pump friction would decrease and the MPRL would increase. When the MPRLs were evaluated for the pumps

	Field Test #1	Field Test #2
PPRL	10399	20479
MPRL	2966	7972

The difference in the MPRL between the field tests is 5000 Ibs. Field Test #1 had the pump set at 2520 as compared to 4994 for Field Test #2. There were 2474' of additional 1" rod in the second field test that have a buoyant weight of 6265 lbs. Essentially the difference in loads can be attributed to the weight of the rod string. The other difference between the field tests is that the tubing in Field Test #1 was unanchored and then anchored in Field Test #2. Future field tests should not use pressure to simulate deeper wells and have the tubing anchored in order to correlated system friction with increasing pump clearance.

Horsepower

Figure 14 Polished Rod Horsepower versus clearance
Figure 15 **KW** (Nabla) versus clearance
Figure **16** PRHP/BFPD versus clearance

Field Test #2			
Test	clearance	PRHP	KW
7	0.0037"	17.1	18.5
2	0.0058"	16.2	17.0
3	0.0086"	17.7	18.9
4	0.0105"	15.9	17.2
5	0.0170"	15.8	17.5
6	0.0209"	15.5	16.5

During the test a card was selected to calculate the KW and the polished rod horsepower for each case and these results are shown in Figures 14 and 15. In the second field test the measurements made at a clearance of 0.0086" are high due to the filters being plugged when the data was recorded. Discounting the data at 0.0086", the polished rod horsepower is essentially flat at higher pump clearances (15.9, 15.8 and 15.5). There is a slightly higher horsepower increasing with decreasing clearances (16.2 HP at 0.0058" and 17.1 hp at 0.0037"). At the lower clearances the PRHP **is** approximately 3 to 8% more than at the higher clearances. The KW measurements, after discounting the 0.0086" data, are flat except at the tightest clearance of 0.0037" which required approximately 1.5 additional KW (increase of 8.5%). There appears to be some additional HP required at the smaller clearances. However, at the highest clearances the power does not change with clearance. The lack of any change in power required at the higher clearances can be explained as the pumping unit is required to do the same amount of work on each stroke regardless of the amount of slippage. Since the fluid load remains the same regardless of the amount of slippage, the same amount of work is performed on each stroke. The polished rod horsepower per barrel of fluid produced increases as the pump clearance (fluid slippage) increases as shown in Figure 16.

While the power cost per barrel of fluid produced increases as fluid slippage increases there are offsetting operating cost savings from less pump friction and reduced sticking that should be considered.

System Friction

Table 3 Card analysis and System friction
Figure 17 Residual Friction versus pump clearance
Figure 18 Downhole pump cards versus clearance
Figure 19 Residual Friction calculation
Figure 20 System friction variables versus clearance

There are several components to the system friction in a rod pumped well which include stuffing box friction, rod-on-tubing friction, fluid resistance on the downstroke and pump drag. In both field tests most of the pumping variables (stroke length, SPM, rod string, seating depth) remained the same so the only significant change was the pump clearance. Field Test #1 attempted to use back pressure to simulate higher fluid loads on the plunger and deeper seating depths. This method was inadequate to determine the impact of plunger drag. The second field test used a constant tubing pressure and tried to keep all the pump variables constant to observe the impact of pump clearances. There was one instance where the surface pressure was increased due to plugging of the surface filter. Another impact could be the stuffing box since a procedure was not used to attempt to keep the same amount of stuffing box friction.

As already mentioned there are several measured variables that can be used to evaluate the system friction as the clearance was changed in the pump, including peak and minimum polished rod loads, power consumption, residual friction and analysis of the downhole cards (net stroke length and drag). Analysis of the downhole cards (Figure 18) did not indicate a difference in friction. The cards did change shape as the fluid slippage increased with increasing clearance.

Residual friction is the load difference between a standing valve check and a leaked off traveling valve. This friction is the sum of the stuffing box, rod drag and pump friction. Since all of the variables remained the same, any difference could be attributed to the change in pump drag. The amount of residual friction is recorded in Table 3 and presented graphically in Figure 17. As these data indicate, there is a substantial increase in the residual load with pumps that have a clearance smaller than 0.0086". At the smallest clearance of 0.0037" there is an increase in residual friction of approximately 1100 lbs.

Although analysis of the downhole card could not clearly measure a difference in pump friction, the increase in net stroke length with increasing clearance clearly shows that there is additional pump drag with tighter clearances. In the second field test the pump drag increases significantly as the pump clearance is less than 0.008". Figure 20 compares the many different indicators and compares to the residual friction.

Erratic valve action

Figure 21 Minimum Polished Rod Load versus clearance for the high pressure case. Example of Erratic Valve Action
Figure 22 Peak Polished Rod Load versus clearance for the high pressure case. Example of Pump Sticking.

Two figures from Progress Report #2 were included to illustrate the impact that plunger sticking can have on the PPRL and late standing valve seating can have on the MPRL. The reduction in the MPRL due to trash and delayed standing valve seating was 800 to 1200 pounds. The PPRL for increased by 1500 pounds due to sticking.

Field Application of Large Clearance Pumps

Table 4 Summary of the Field Application of Large Clearance Pumps – South Justis Unit
Table 5 Details of the Field Application of Large Clearance Pumps – South Justis Unit
Figure 23 Pump Efficiency versus Clearance for Field Test #2 and South Justis Unit
Figure 24 Fluid Slippage versus Clearance – Field Application with 1.5" pumps
Figure 25 Fluid Slippage versus Clearance – Field Application with 2.0" pumps

ARCO has been utilizing larger clearance pumps in the South Justis field to help resolve some operating problems. The primary probiems have been repeated rod failures. Tables **4** and *5* provide information on these installations. Even with the large clearances, these pumps have had high pump efficiencies. Although these wells operate at high water cuts the pump efficiencies are high. This emphasizes the impact of the in-situ viscosity on fluid slippage. Figure **23** compares the pump efficiencies of the larger clearance pumps at South Justis with Field Test #2. Most of these pumps had efficiencies greater than what was recorded in the second field test. This occurred even for 2" pumps when the field test was conducted with 1.5" pumps.

The lowest efficiency occurred in well B-**18** at 58%. This well was pulled and the teardown of the pump revealed that there was a leaking traveling valve.

Utilizing the data in Table 4, a Method 1 calculation can be used to determine fluid slippage. The difference between the pump displacement and the production corrected for run time is assumed to be fluid slippage. Only data for wells in a "pumped-off' condition were shown in Figures 24 and 25 to have a relatively constant plunger differential (2645 psi) to compare to the equations. The standard plunger length in this field is 48 inches.

These figures show the impact of viscosity on both the ARCO-HF and the Robinson-Reekstin equation and how each equation compares to the field fluid slippage. The minimum viscosity would that of water at 100 F at 0.69 centipoise. Additional viscosities of 1.0 and 1.5 are also presented with each of the equations. It should be noted that these changes in viscosity have a significant impact on the fluid slippage. In all of the wells the water cut is in excess of 90%.

Consideration should be given to the accuracy of the data. For field calculated Slippage, the pump displacement assumes complete barrel fillage. Both test accuracy and the percent run time can have an impact on the field calculated fluid slippage. A few data points show the error band in fluid slippage if the test production was off +/- 10%. The run time percentage did not appear to impact the fluid slippage. Pumping speed did not correlate with pump efficiency for the 1.5" pumps but there was an general increase in pump efficiency with increasing strokes per minute for the 2" pumps.

Based on these few data points it appears that the calculated fluid slippage is generally "bracketed" between these two equations with the Robinson-Reekstin on the low side and the ARCO-HF equation on the high side. However, the ARCO-HF equation indicates there is a much more dramatic change in fluid slippage with changes in plunger length than the Robinson-Reekstin equation.

Observation and Recommendations

Leakage

Observations:

(1) Difference in lab and field data – There is a definite difference in the fitted curve exponent between the field fluid slippage and that measured in the lab.

(2) Pressure, viscosity and length scale linearly – The data was grouped between the field tests and lab tests based on ratios of plunger lengths, plunger differential pressure and viscosity.

(3) Viscosity can have a significant impact.

(4) Field application of larger clearance pumps in **SE** New Mexico indicates both the new empirical equation and the Robinson-Reekstin equation provide reasonable estimates of fluid slippage.

   a) Fluid slippage is generally "bracketed" between these two equations with the Robinson-Reekstin on the low side and the ARCO-HF equation on the high side.
   b) Run time did not appear to impact the fluid slippage.
   c) Pumping speed did not correlate with pump efficiency for the 1.5" pumps but there was an general increase in pump efficiency with increasing strokes per minute for the 2" pumps.

Recommendation:

(1) Use both the ARCO-HF and the Robinson-Reekstin equations to estimate the range of fluid slippage.

(2) Use water viscosity (worst case). – Of all of the variables in the slippage equation the in-situ viscosity is by far the hardest to obtain. Decisions to open pump clearances should be based first on using water viscosity at the downhole temperature.

(3) Evaluate longer length plungers. – After the leakage has been determine using water viscosity. Consider using a longer plunger to reduce slippage especially if solids are a problem in the producing well. The ARCO-HF equation indicates there is a much more dramatic change in fluid slippage with changes in plunger length than the Robinson-Reekstin equation.

(4) Need additional field and lab data to increase understanding. This should not be the end of testing of different clearance pumps. These tests have been conducted with only one size pump, one SPM and very limited changes in viscosity.

   a) Different size plungers, pumping speeds and viscosities.
   b) In-situ viscosity determination

Rod Loads

MPRL and PPRL

Observations:

(1) MPRL increases and the PPRL decreases with increasing clearance.
(2) Delayed standing valve closing can significantly reduce the MPRL.
(3) Solids and plunger sticking can significantly increase the PPRL.
(4) Delayed standing valve closing and plunger sticking are not intimately related in that delayed valve action can occur without plunger sticking.

Recommendation:

(1) Need to consider impact of higher viscosity, erratic valve action and solids. Should expect in these cases an increase in MPRL with increasing clearance.

Residual Friction

Observations:

(1) Higher *system* friction with smaller pump clearances (<0.008"). In the field test the increase pump drag was in excess of 1100 pounds. At a pump clearance of 0.008" the pump drag was minimal.
(2) Residual friction calculations and net stroke length versus clearance collaboratively indicate that there is increased pump friction as the pump clearance is reduced.

Recommendation:

(1) Target pump clearances starting at 0.007".
(2) Need better understanding of system frictional components:
    a) stuffing box
    b) rod-on-tubing drag
    c) pump drag
(3) **A** correlation of pump drag versus clearance is needed to improve the design capabilities of predictive programs to assist in rod string design.

Net Stroke Length

Observations:

(1) Net stroke length increases with increasing clearance
(2) Rate of net stroke length change was greatest at clearances < 0.008"

Recommendation:
(1) Need better understanding of *pump* frictional Components:
    a) Viscous drag (in-situ viscosity)
    b) Sliding friction
    c) Effect of solids

(2) **A** correlation of net pump stroke versus pump clearance is needed to improve the predictive programs.

Power

Observations:

(1) Slight downward trend in PRHP with increasing clearance. Highest PRHP obtained at the tight pump of 0.0037".
    a) Average of all cards for each test
(2) Same trend was not observed in KW measurements except at the tight clearance pump.
    a) Smaller sample size (1 card per test)
(3) The lack of any change in power required at the higher clearances can be explained as the pumping unit is required to do the same amount of work on each stroke regardless of the amount of slippage.
(4) The polished rod horsepower per barrel of fluid produced increases as the pump clearance (fluid slippage) increases.

Recommendation:

(1) While the power cost per barrel of fluid produced increases as fluid slippage increases there are offsetting operating cost savings from less pump friction and reduced sticking that should be considered.

Acknowledgements

Thanks to the many people have participated in this work:

Texas Tech University - ALEOC for funding of the field tests.

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Harbison Fisher - for providing the pumps and shop support.

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2) Coberly, C. J. : *Theory and Application of Hydraulic Oil Well Pumps,* Kobe Inc., Huntington Park, California (1961)
3) "Heat Transfer and Pressure Drop in Annuli," by E. S. Davis, Trans. ASME, vol. 65, 1943, pp. 755-760
4) Glenn M. Stearns, a progress report, "An Evaluation of the Rate of Slippage of Oil Past Oil-Well Pump Plungers," Drilling and Production Practice, 25-33 (1944).
5) "Minimizing Slippage in Subsurface Pumps," Petroleum Engineer, April 1960, by R. W. Reekstin.
6) Bruce H. Robinson, "Economics of Pumping," Drilling and Production Practice, 25-33 (1944)
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11) Patterson, J. C. and Williams, B.J., A Progress Report on "Fluid Slippage in Down-Hole Rod-Drawn Oil Well Pumps", presented at the Southwestern Petroleum Short Course, April, 1998.
12) Patterson, J. C. et al, Progress Report #2 on "Fluid Slippage in Down-Hole Rod-Drawn Oil Well Pumps", presented at the Southwestern Petroleum Short Course, April, 1999.
13) Nolen, K.B. and Gibbs, S. G.: "Quantitative Determination of Rod-Pump Leakage with Dynamometer Techniques" SPE Production Engineering, August 1990, 225 – 230.

Table 1 - Test Equipment

Field Test #1

Pumping Unit	456 Mark II
Stroke Length	144"
Strokes per Minute	6.7
Tubing Size	2-7/8" unanchored
Casing Size	8 5/8" w/ bridge plug above perforations
Rod String	1"
Pump Setting Depth	2520 feet
Tubing Pressure	Three test cases at 40, 560 and 1060 psi
Pump Size	1.75" RHBC. See table below for valve patterns
Well Fluid	Fresh water circulated from tubing back down casing

Test	Clearance (in.)	Valve Pattern
1-3	.0052	API double valved TV and SV
4-6	.0086	Calif. double valved TV and SV
7-9	.0102	Calif. double valved TV and SV
10-12	.0166	Calif. double valved TV and SV
13-15	.0052	Calif. double valved TV and SV

Field Test #2

Pumping Unit	456 Mark II
Stroke Length	144"
Strokes per Minute	6
Tubing Size	2-7/8" anchored
Casing Size	" w/ bridge plug above perforations
Rod String	1"
Pump Setting Depth	4994'
Tubing Pressure	0-60 psi
Pump Size	1.75" RHBC. See table below for valve patterns
Well Fluid	Fresh water circulated from tubing back down casing

Test	Clearance (in.)	Valve Pattern
1	.0058	API single valved TV and SV
2	.0058	Calif. single valved TV and SV
3	.0086	Calif. double valved TV and SV
4	.0105	Calif. double valved TV and SV
5	.0170	Calif. double valved TV and SV
6	.0209	Calif. double valved TV and SV
7	.0037	Calif. double valved TV and SV

Table 2 - Fluid Slippage and Pump Efficiency

Field Test #1
California balls and seats

(1) Test	(2) clearance	(3) Measured Surface Kate BPD	(4) Calculated downhole stroke using the pump card, inches	(5) Calculated pump displacement BPD	(6) Calculated Fluid slippage (5) – (3) BPD Method 1	(7) Nabla of change of TV load slippage BPD Method 2	(8) Fluid slippage calculated with Robinson-Reekstin equation BPD Method 3	(9) Pump efficiency, (3)/(5)
High Tubing Pressure Case – approximately 900 psi								
15	0.0052"	286	136.8	327	41	14	8	87%
9	0.0102"	241	137.2	328	87	51	70	74%
12	0.0166"	188	138.6	332	144	90	339	57%
Medium Tubing Pressure Case – approximately 400 psi								
14	0.0052"	264	138.7	332	68	11	5	80%
8	0.0102"	269	139.2	333	64	32	47	81%
11	0.0166"	201	140.1	335	134	66	229	60%
Low Tubing Pressure Case - approximately 40 psi								
13	0.0052"	311	140.3	336	25	10	4	93%
7	0.0102"	276	140.9	337	61	26	33	82%
10	0.0166"	215	141.4	338	123	78	158	64%

Field Test #2

(1) Test	(2) clearance	(3) Measured Surface Rate BPD	(4) Calculated downhole stroke using the pump card, inches	(5) Calculated pump displacement BPD	(6) Calculated Fluid slippage (5) – (3) BPD Method 1	(7) Nabla rate of change of TV load slippage BPD Method 2	(8) Fluid slippage calculated with Robinson-Reekstin equation BPD Method 3	(9) Pump efficiency, (3)/(5)
1	0.0058"	286	134.0	312	26	17.5	11	92%
2	0.0058"	274	136.8	320	46	21.0	13	86%
3	0.0086"	246	138.2	326	80	58.1	43	75%
4	0.0105"	217	138.5	326	109	120.0	88	67%
5	0.0170"	146	140.0	329	183	177.0	386	44%
6	0.0209"	83	140.4	328	245	253.0	988	25%
7	0.0037"	292	133.9	312	20	5.6	3	94%

Table 3 - Card Analysis and System Friction

Test	clearance	Fluid load	Downstroke friction "card belly"	Residual Friction	PRHP	Net stroke length	Comments
7	0.0037"	4800	1590	2100	17.1	133.9	
2	0.0058"	4800	930	1380	16.2	136.8	
3	0.0086"	5450	1060	968	17.7	138.2	Plugged filter
4	0.0105"	4800	1000	1015	15.9	138.5	
5	0.0170"	4800	990	1030	15.8	140.0	
6	0.0209"	4760	1300	850	15.5	140.4	

Table 4 - Field Application of Large Clearance Pumps - South Justis Unit

Number of Pumps	Total pump clearance	Average Pump Efficiency
5 – 1.5"	-7	96%
2 -1.5" and 5 - 2.0"	-8	73%
7 -1.5" and 6 - 2.0"	-9	84%
3 - 2.0"	-10	87%
3 - 2.0"	-11	94%

Table 5 - Details of the Field Application of Large Clearance Pumps - South Justis Unit

WELL	Pump CAP	Run time (%)	PROD BPD	PE (%)		PUMPING UNIT				SPM	SL	TBG	PMP	TOTAL FIT	Days since install to 10/15/99
F13	398	100%	388	97%		M	456	256	144	11.0	144	2 3/8	1 1/2	-7	24
F27	353	100%	333	94%		M	640	256	144	9.8	144	2 3/8	1 1/2	-7	37
G27	370	100%	363	98%		M	456	253	144	10.3	144	2 3/8	1 1/2	-7	51
H27	339	61%	205	99%		M	640	365	168	8.2	168	2 3/8	1 1/2	-7	17
H29	326	67%	198	91%		M	320	304	120	11.8	120	2 3/8	1 1/2	-7	148
				96%											55
B18*	377	100%	220	58%		C	640		120	7.8	120	2 7/8	2	-8	254
D27	525	62%	243	75%		C	640	365	168	8.5	144	2 7/8	2	-8	248
E25	385	58%	178	80%		M	456	256	144	10.8	144	2 3/8	1 1/2	-8	34
F14	618	79%	369	76%		M	640	305	144	10.0	144	2 7/8	2	-8	69
F21	603	71%	299	7Mb		C	912	365	168	9.5	144	2 7/8	2	-8	300
F25	583	49%	181	63%		M	610	305	168	92	149	2718	2	-8	272
G17	442	85%	33;	89%		M	640	256	168	10.5	168	2 3/8	1 1/2	-8	203
				73%											197
C11	244	18%	40	91%		C	320	256	120	9.8	102	2 3/8	1 1/2	-9	92
D25	652	65%	396	93%		M	912	305	168	9.1	168	2 7/8	2	-9	190
E19	204	96%	149	76%		M	160	213	86	10.6	86	2 3/8	1 1/2	-9	153
E23	436	100%	437	100%		C	912		168	8.6	168	2 3/8	1 1/2	-9	35
E24	596	93%	523	94%		M	640	305	168	8.4	149	2 7/8	2	-9	31
F19	542	71%	359	93%		M	640	305	168	9.1	148	2 7/8	2	-9	57
F22	658	100%	650	99%		C	912	365	168	8.8	168	2 7/8	2	-9	171
F28	331	81%	247	92%		M	320	256	144	10.9	128	2 3/8	1 1/2	-9	41
G15	237	66%	113	72%		M	228	213	120	9.8	104	2 7/8	1 1/2	-9	151
G181	378	58%	167	76%		M	456	256	144	10.3	144	2 3/8	1 1/2	-9	45
G26	305	54%	123	75%		M	320	256	120	7.8	103	2 7/8	2	-9	212
G28	332	100%	269	81%		C	456	305	144	10.0	120	2 3/8	1 1/2	-9	85
G29	642	37%	220	93%		M	912	305	168	9.2	168	2 7/8	2	-9	162
				84%											110
D16	740	100%	702	95%		M	912	305	168	10.3	168	2 7/8	2	-10	72
E201	702	100%	526	75%		C	912	365	168	9.2	168	2 7/8	2	-10	98
E21	653	100%	683	105%		C	912	365	168	10.6	144	2 7/8	2	-10	9
				87%											60
C19	543	100%	464	85%		M	640	305	168	8.2	166	2 7/8	2	-11	20
D20	672	100%	646	96%		C	912	365	168	8.9	168	2 7/8	2	-11	94
E22	459	100%	488	106%		M	640	305	144	9.3	120	2 7/8	2	-11	123
				92%											79

* B 18 – found valve problem during pump teardown

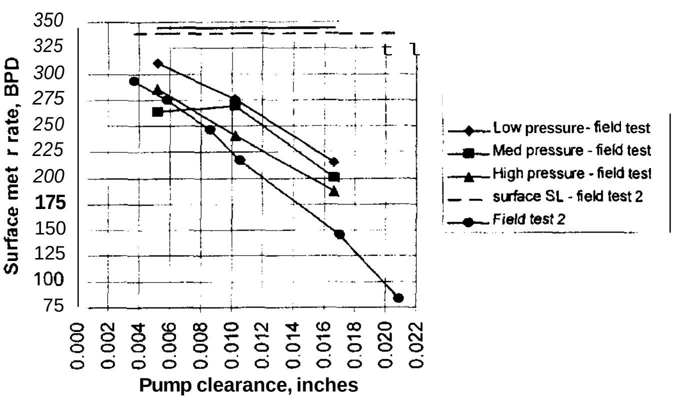


Figure 1 - Surface Metered Rate vs. Pump Clearance
Field Tests 1 and 2

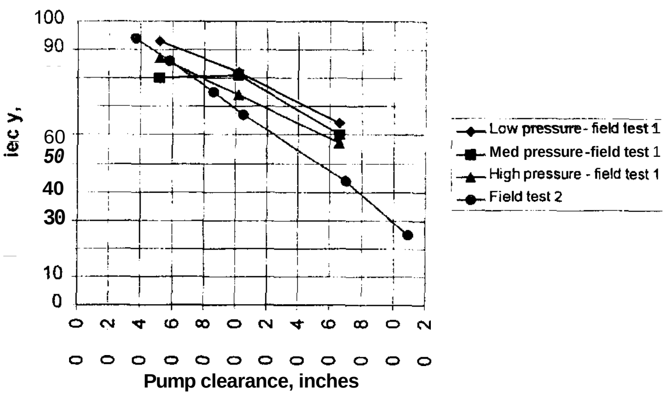


Figure 2 - Pump Efficiency vs. Pump Clearance
Field Tests 1 and 2

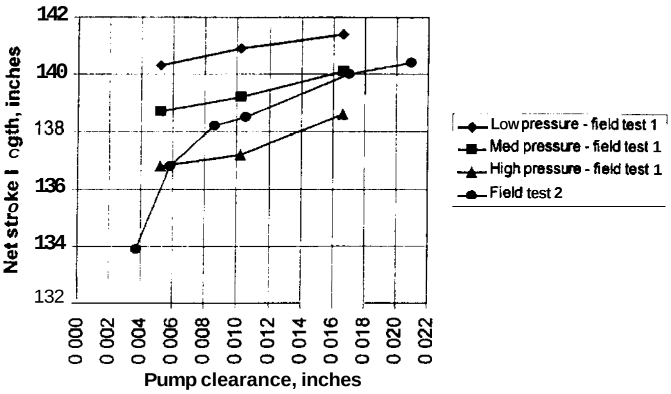


Figure 3 - Net Stroke Length vs. Pump Clearance
Field Tests 1 and 2

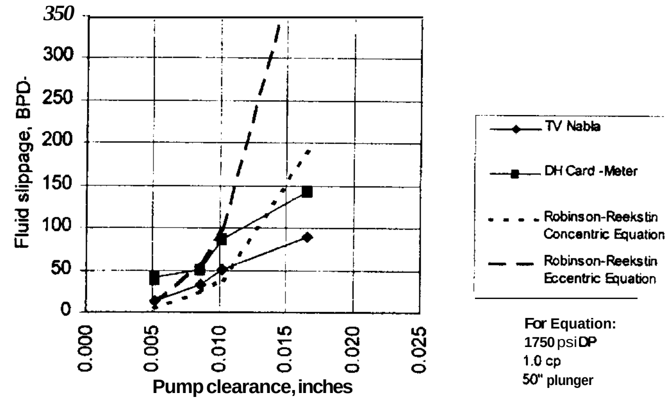


Figure 4 - Fluid Slippage - Field Test #I
High Pressure Case

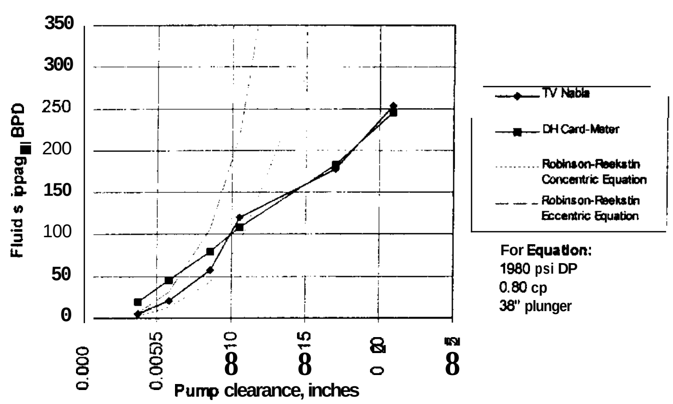


Figure 5 - Fluid Slippage - Field Test #2

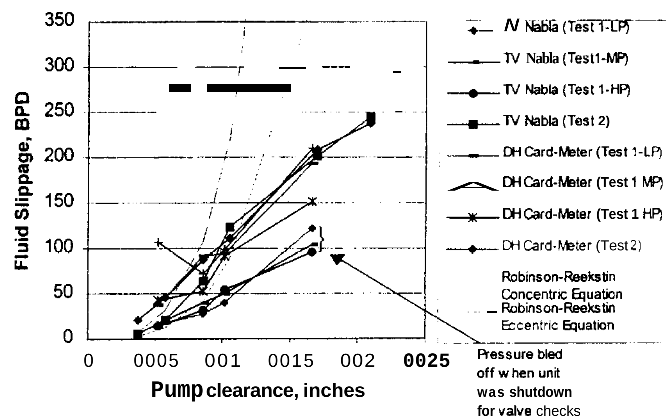


Figure 6 - Fluid Slippage - Test #1 and #2 Combined
Normalized to 2000# DP, 0.8 cp visc and 38" plunger

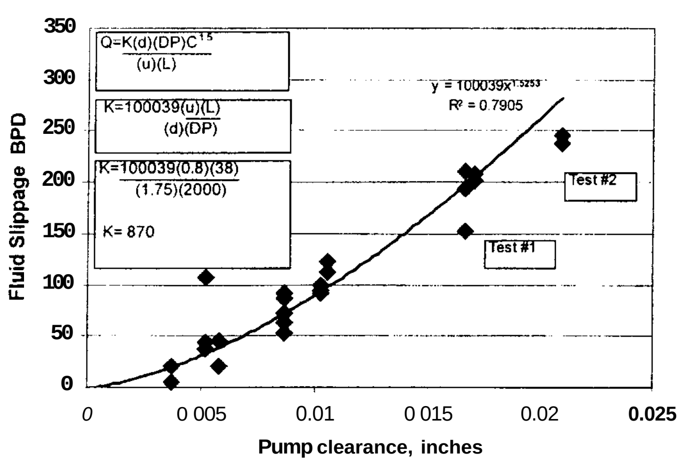


Figure 7 - Field Test #1 and #2 Combined
Normalized to 2000# DP, 0.8 cp visc and 38" plunger

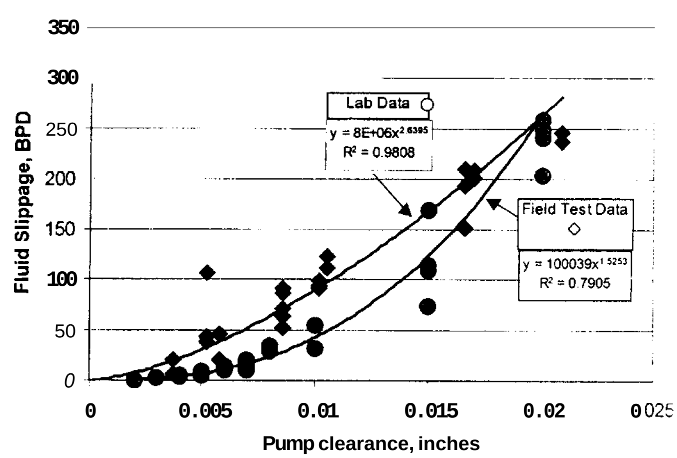


Figure 8 - Combined Lab and Field Data
Normalized to 2000# DP, 0.8 cp visc and 38" plunger

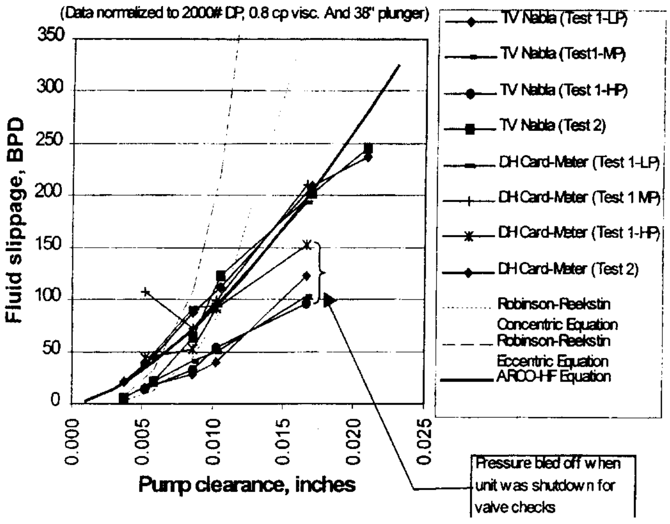


Figure 9 - Fluid Slippage - Test #1 and #2 Combined

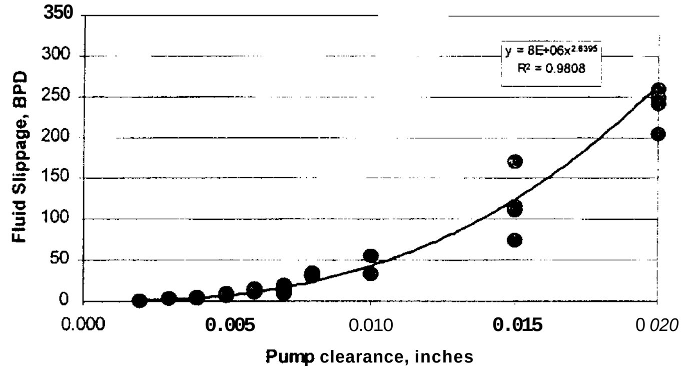


Figure 10 - Lab Test
Normalized to 2000# DP, 0.8 cp visc and 38" plunger

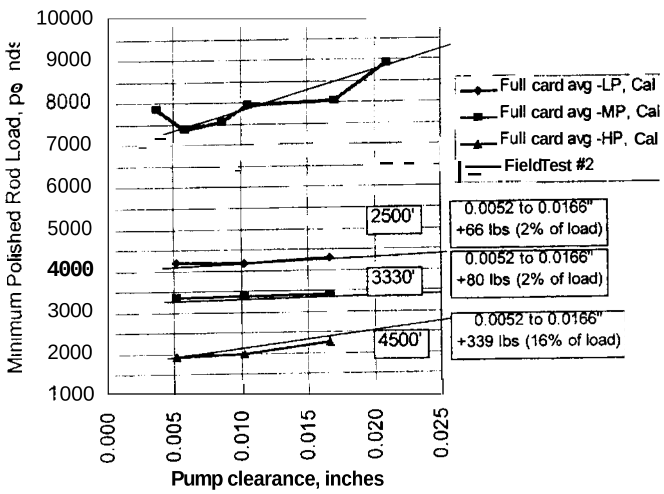


Figure 11 - MPRL vs. Clearance for a 1.75" Plunger

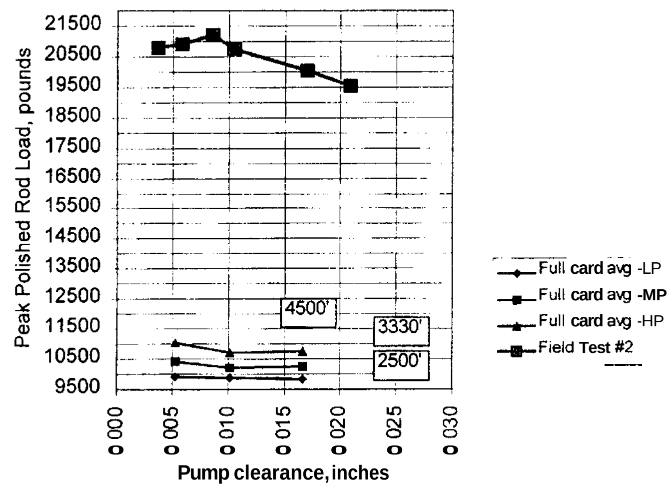


Figure 12 - PPRL vs. Clearance for a 1.75" Plunger

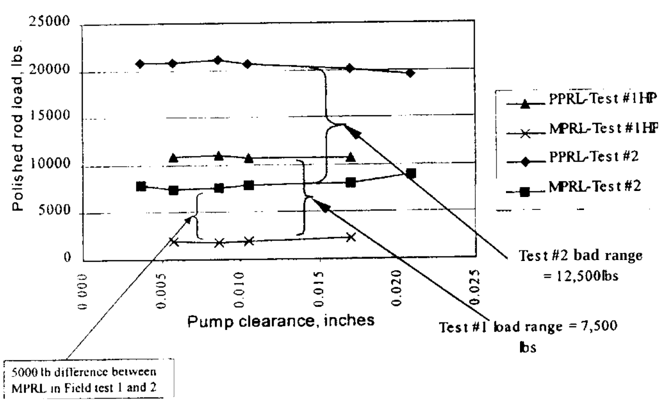


Figure 13 - Polished Rod Loads -
Field Test #1 & #2

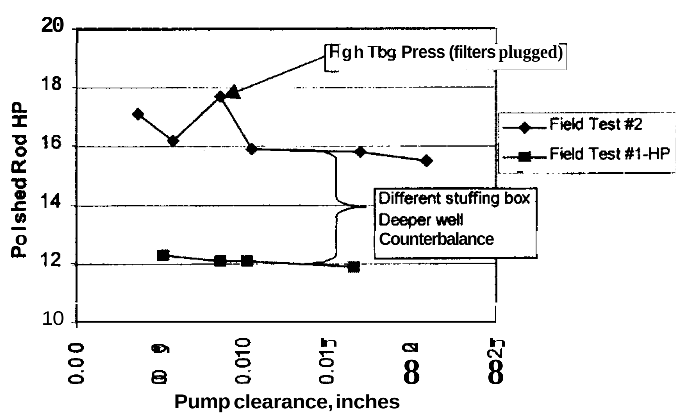


Figure 14 - Polished Rod Horsepower -
Field Test #1 & #2

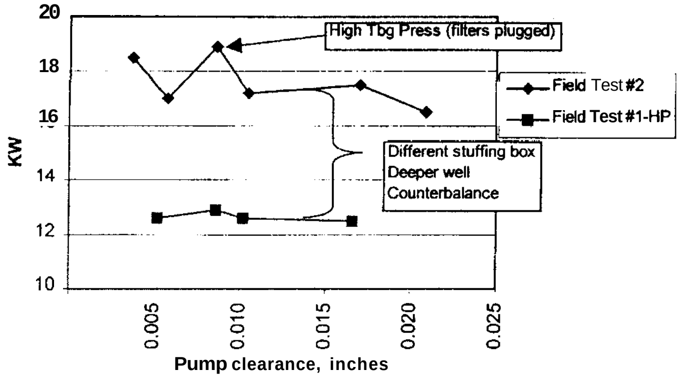


Figure 15 - Nabla KW Measurements - Field Test #1 & #2

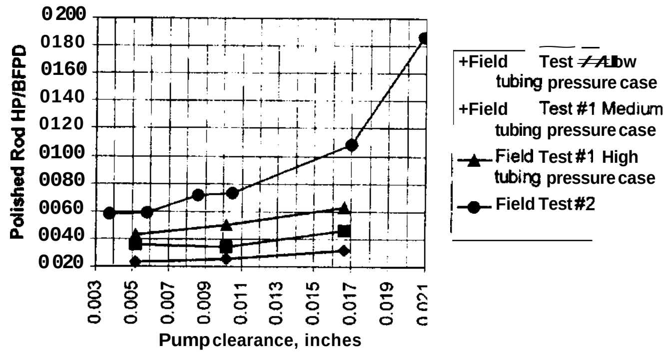


Figure 16 - Polished Rod Horsepower/BFPD versus Clearance

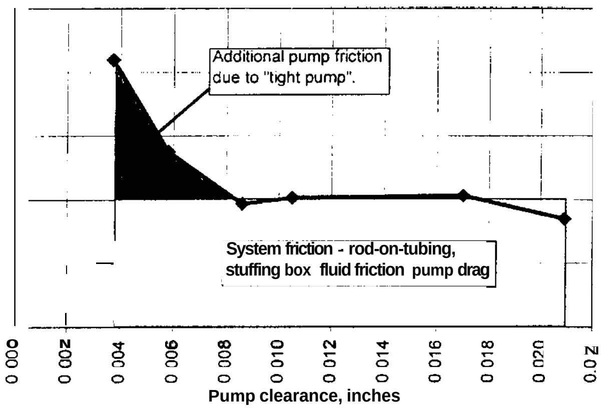


Figure 17 - Residual Friction vs. Pump Clearance Field Test 2

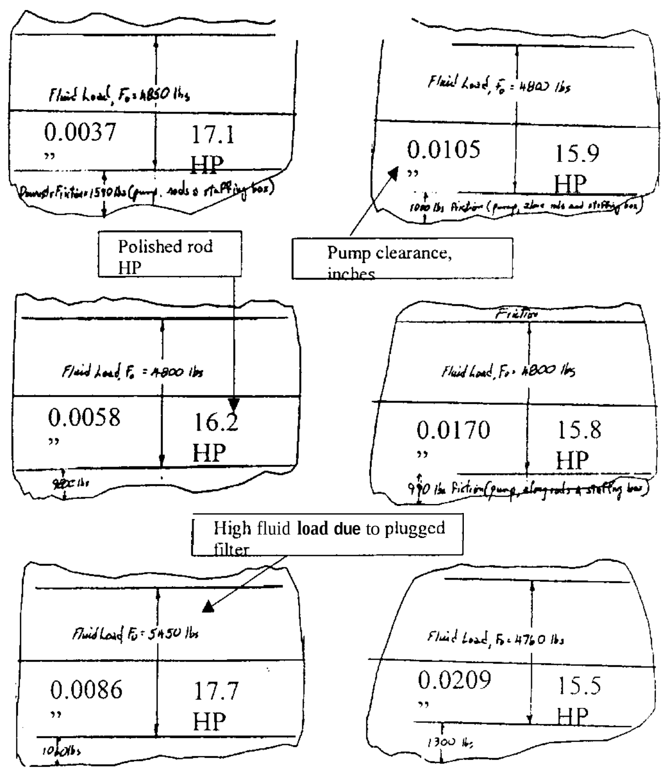
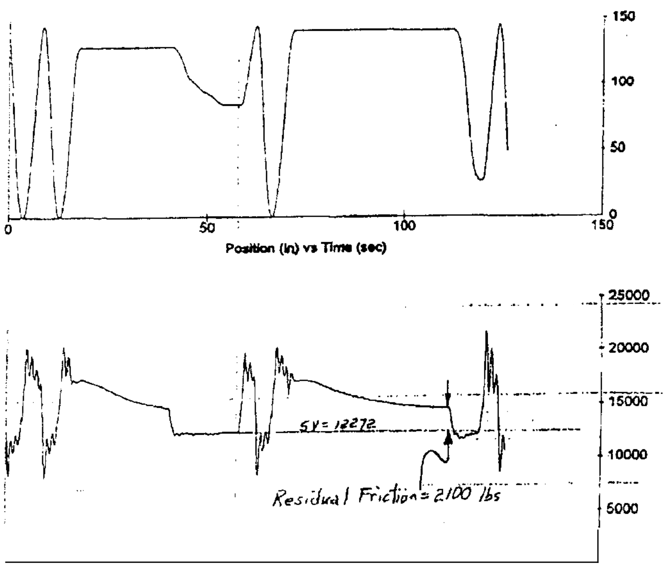


Figure 18 - Downhole Pump Cards vs. Clearance



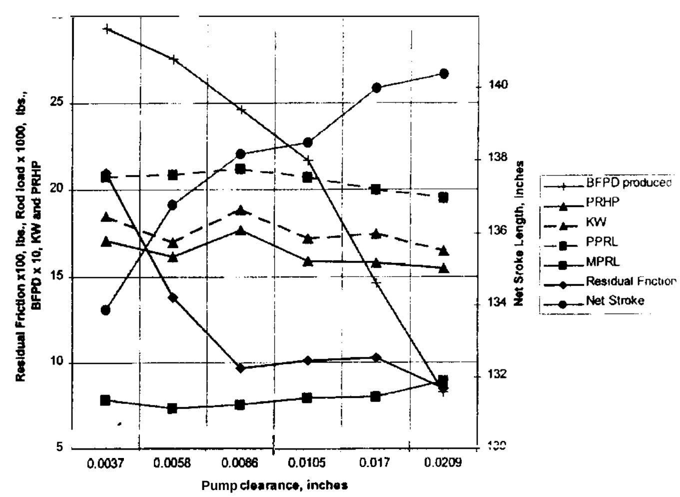
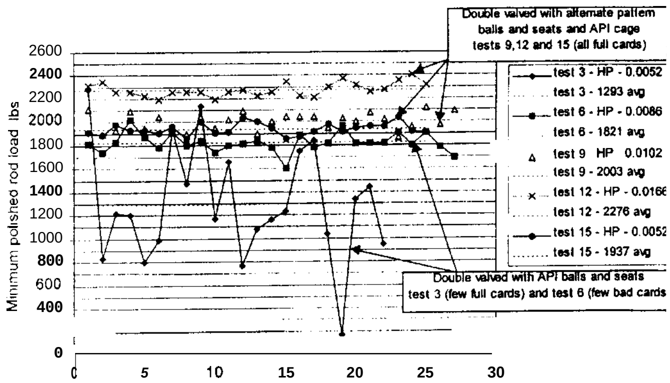


Figure 20 - System Friction Variables vs. Clearance



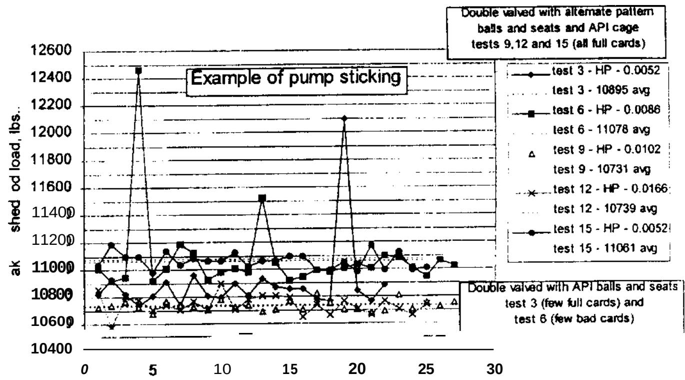


Figure 22 - PPRL for High Tubing Pressure Cases
900 psi approximately 4500'

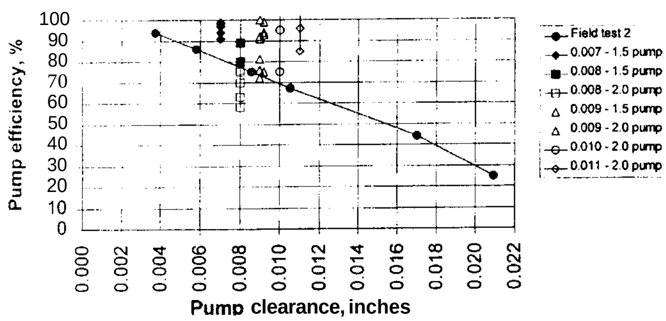


Figure 23 - Pump Efficiency vs. Pump Clearance
Field Test 2 and South Justis Unit

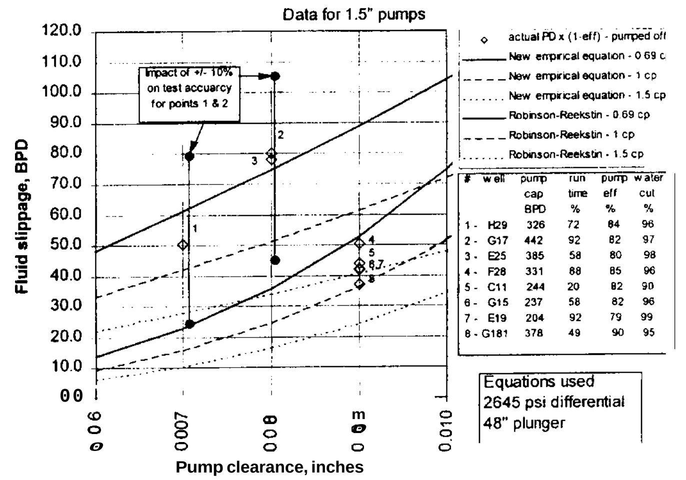


Figure 24 - Field Application of Large Clearance Pumps
Data for 1.5" pumps

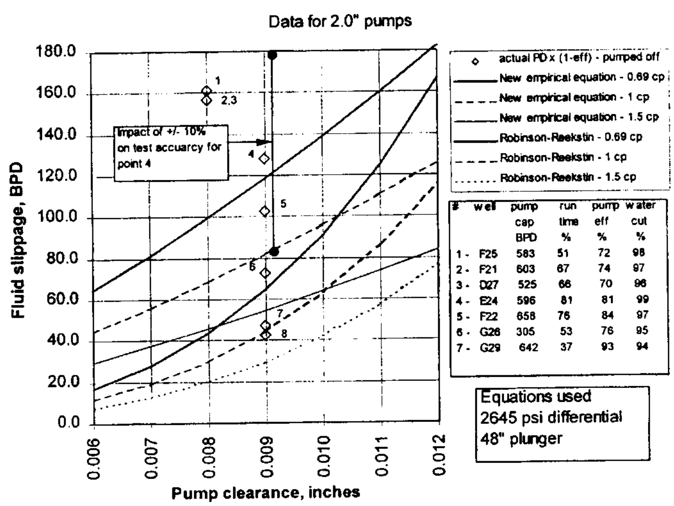


Figure 25 - Field Application of Large Clearance Pumps
Data for 2.0" pumps