Progress Report #2 on "Fluid Slippage in Down-Hole Rod-Drawn Oil Well Pumps"

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Abstract and Scope

This paper will present results of a field slippage test and compare these results with laboratory testing of pump slippage presented in the 1998 Southwestern Petroleum Short Course paper. This is progress report #2, with the ultimate goal being to present an empirical equation which will accurately represent the down-hole slippage. The current results should be useful to operators for selection of clearances between metal plungers and barrels.

Objective

During the presentation of the first progress report, many questions were asked regarding the applicability of the lab data and the Robinson-Reekstin equation, to actual pumping conditions. It was stated in one question and answer session that "Pumps installed with clearances greater than 0.008" would not lift fluid to the surface." Therefore, the objective of this interim report was to compare the lab data to results from actual pumping conditions.

Summary of Results

The field fluid slippage test data continues to verify the Robinson-Reekstin equation which was selected based upon the laboratory pump slippage data presented in the 1998 Southwestern Petroleum Short Course paper. 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 matched the lab data below a clearance of 0.010".

Based on field testing, the Robinson-Reekstin equation continues to provide 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. The test well was able to produce fluid, although at a reduced volumetric efficiency, at a pump clearance of 0.0166" when this equation predicted that the fluid slippage would be in excess of the pump capacity.

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". A pump is considered to be worn out when the plunger and/or barrel wears to a point that the fluid slippage becomes large enough to materially affect 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. However, there is a limit to the clearance that can be used while maintaining reasonable fluid slippage.

Historical equations have taken the general form of the equation listed below with slight differences in the constant (K) and the exponents on the variables in the equation. 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.

As stated in interim report #1, the Robinson-Reekstin equation provided the best fit of the lab data up to a clearance of 0.008" to 0.010". Their empirical equation is as follows:

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

where: K = constant = 2.8×10^{6}, 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
V = viscosity in centipoise
P = differential pressure across the plunger in psi

Field Test Setup and Analysis

A field test was conducted to measure fluid slippage. A well that was temporarily abandoned was utilized to measure the fluid slippage using pumps with different clearances. Table 1 summarizes the equipment used in the field test.

A test pump was inserted and the well was pumped through a positive displacement meter and a back-pressure 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. The surface rates recorded for each series of tests are shown in the Figure 1 and Table 2.

Fluid Slippage

Fluid slippage was calculated by three different methods using the data from the test 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 to calculate the plunger differential pressure.

Test data and calculated values are presented in Table 2 and graphically for the high-pressure case (900 psi tubing pressure or 1765 psi plunger differential) in Figure 2.

The only dynamic method uses the fluid displacement based on the net downhole stroke minus the surface meter reading (Method 1). Nabla's method of load change on the traveling valve is done during a traveling valve check with the plunger stationary. 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.

Valve stops (Method 2) 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 Figure 2 and Table 2. These slippage values under-predicted the fluid slippage as measured during the test using Method 1 at all pump clearances.

It will be noted in Table 2 that there is a difference between the fluid calculated by the Robinson-Reekstin equation (Method 3) and the slippage calculated using the downhole pump displacement minus the surface meter (Method 1). The calculated fluid slippage using Method 1 diverges from the Robinson-Reekstin equation past a clearance of 0.010" as shown in Figure 2. Also, the Robinson-Reekstin equation predicts that no fluid would be produced to the surface with a clearance of 0.0166", but the well was in fact, pumping approximately 188 BFPD with the high tubing pressure (900 psi). To calculate the fluid slippage using the Robinson-Reekstin equation and represent the downhole pumping conditions, a good representation of the plunger pressure differential is required. The lab data presented in Interim Report #1 showed that the fluid slippage matched the Robinson-Reekstin equation, which was the most conservative of the historical equations. Lab tests were conducted with a "known" plunger differential pressure. During the field test a surface pressure recorder was used to measure the tubing pressure throughout each test and the average pressure was used to calculate fluid slippage. It should be noted that there were pressure swings during the pumping cycle with the maximum tubing pressure ranging from 1.0 to 2.0 times the average pressure used in the equation. Likewise the fluid production changed during the pumping cycle with the majority being produced on the downstroke. The PD meter was proved after the test and found to be accurate. Table 2 and Figure 2 shows that the Robinson-Reekstin equation under-predicted the fluid slippage below a clearance of 0.010" and at larger clearances over-predicted the fluid slippage as calculated using Method 1.

In addition to the test data, the previous lab data, adjusted for downhole conditions, was plotted for comparison and is shown in Figure 3. The same departure from the fluid slippage equation is also evident on the lab data.

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.

Minimum Polished Rod Loads

As the pump clearance increases, one might expect that the pump friction to decrease and the MPRL would increase. When the MPRLs were evaluated for the pumps using alternate pattern balls and seats, it was found that only the high tubing pressure case had a significant increasing MPRL with increasing clearance as shown in Figure 4.

This data does not include pumps with smaller clearances below 0.005" which have been typical clearances used in rod pumps. If pumps with smaller clearances were run in these tests there might have been more drag (lower MPRL) with these pumps.

Peak Polished Rod Loads

The average PPRLs for the series of cards were also analyzed and show a decreasing PPRL with increasing clearance to 0.010". Data from the 0.0166" clearance pumps have a PPRL similar to the 0.010" pump. See Figure 5. The "flattening" out of the PPRL versus clearance occurs at the same point that the fluid slippage departs from the fluid slippage curve. It should be noted that this is only one data point and that additional field testing will be required to confirm this relationship.

Horsepower

During the test a "good card" was selected to calculate the KWH and the polished rod horsepower for each case and these results are shown in Figures 6 and 7. The polished rod horsepower is essentially flat with increases in pump clearance. Regardless of the amount of slippage the pumping unit is required to do the same amount of work on each stroke. The polished rod horsepower per barrel of fluid produced increases as the pump clearance (fluid slippage) increases as shown in Figure 8.

<u>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.</u>

Erratic valve action

The traveling and standing valves were double valved in the test to minimize the chance that valve fluid slippage would be a problem. However, circulating the well during the test caused "trash" to be pumped which significantly impacted the pump performance. The first two pumps used API pattern balls and seats and the other pumps used alternate or California pattern balls and seats. Balls used in Alternate or California pattern valves are 1/16" to 1/8" smaller than the API balls. Numerous surface cards were collected for each pump clearance and tubing pressure. The pumping action with the API pattern pumps was sporadic as indicated by the number of the cards that had incomplete fillage. The cards with incomplete fillage had a MPRL that was lower than expected. The MPRL for each of the pressure cases are shown in Figures 9, 10 and 11.

It is interesting to note the impact of pumping "trash" through a pump. There are three possibilities that could have caused the reduced MPRL:

1. Particulate material was trapped between the plunger and the barrel; thus increasing the pump friction and lowering the MPRL.
2. Delayed standing valve closure that allowed the fluid load to remain on the rod string for a longer time on the downstroke.
3. Restricted traveling valve opening which increased the fluid friction on the downstroke.

One pump (0.0052" clearance) was tested with both API pattern valves and alternate pattern valves. Tests 1, 2 and 3 were conducted with the API pattern and tests 13, 14 and 15, which were the last tests run, had alternate pattern valves. In tests 1, 2 and 3, when the pump was free of "trash" and had a full card, the MPRL was very close to the MPRL for the alternate pattern tests 13, 14 and 15. This would tend to indicate that there was not much flow difference on the downstroke between the two styles of valve. Each pump was torn down and inspected after being run. There were some solids in the valve and between the top plunger cage and the plunger but there was no indication of scoring on either the plunger or barrel. Based on this observation it is believed that the sporadic pump action was due to solids hindering valve action. The reduction in the MPRL due to trash was 800 to 1200 pounds. The PPRL for these tests are shown in Figures 12, 13 and 14. There was not as much impact on the PPRL versus the MPRL.

Conclusions

1. Fluid slippage with increased clearances is not as large as previously assumed or predicted in many of the historical equations.
2. The Robinson-Reekstin empirical equation slightly under-predicts fluid slippage up to a pump clearance of 0.010" but greatly over-predicts fluid slippage above these clearances. A new equation is needed to more accurately predict the leakage, especially at clearances between 0.010" to 0.020".
3. The polished rod horsepower is not affected by slippage, but the power per barrel of fluid produced increases as the slippage increases.
4. Erratic valve action can have a significant impact on the MPRL. Problems can be intermittent and may not always be apparent. Valve designs that improve valve operation should be considered.

Additional field and lab testing are planned. The next field test will utilize the same plungers and barrels but will be conducted with the tubing anchored with a pump setting depth of at least 4000'.

Acknowledgements

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TRICO - for providing the pumps and shop support.

Table 1
Test Equipment

Pump unit	456 MarkII
Stroke length	144"
Strokes per minute	6.7
Tubing size	2-7/8" unanchored
Casing size	8-5/8" with bridge plug above perforations.
Rod string	1"
Pump setting depth	2520 feet
Fluid level over pump	500 feet
Tubing pressure	Three test cases at 40, 560, 1080 psi
Pump size	1.75" with doubled valved standing and traveling valves. (Alternate pattern balls and seats)
Pump diametric clearance	0.0052", 0.0086", 0.0102" and 0.0166"
Well fluid	Fresh water circulated from tubing back down casing.

Table 2
Fluid Slippage and Pump Efficiency
California balls and seats

(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 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%

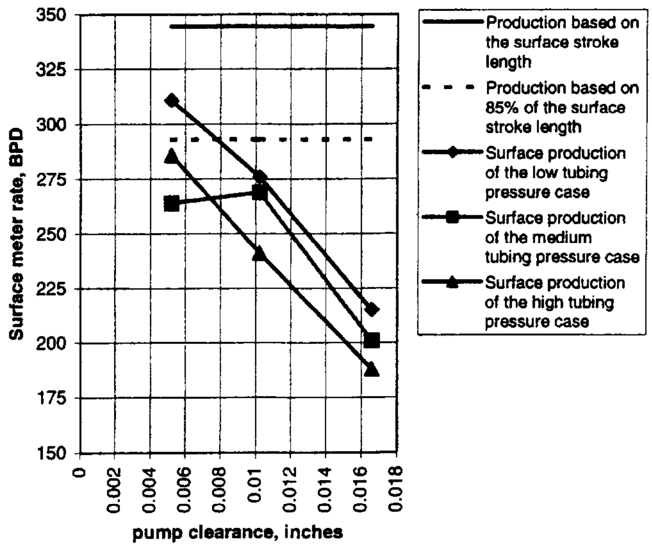

Figure 1 - Surface Metered Rate vs. Pump Clearance
California pattern balls and seats

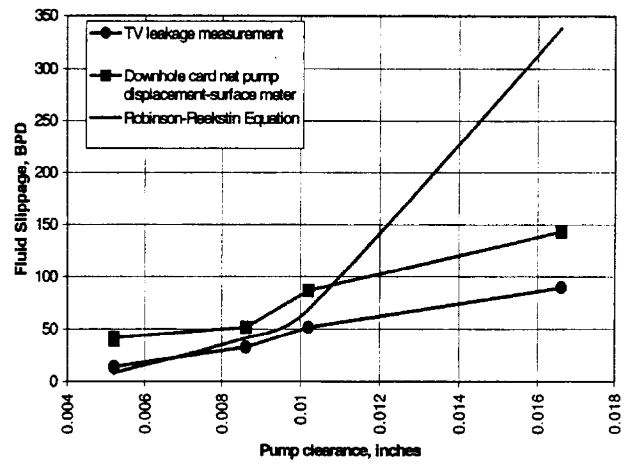

Figure 2 - Fluid Slippage - High Pressure Case
1765 psi plunger differential pressure

Using the surface stroke length of 144", 6.7 SPM and a 1.75" diameter, the pump displacement is 345 BPD.

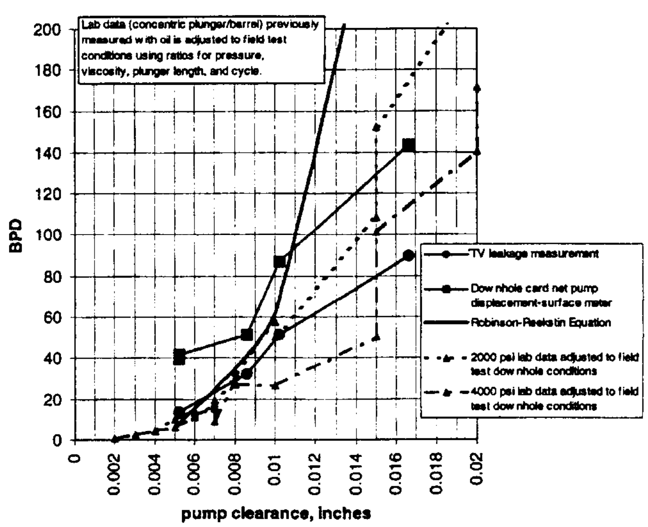

Figure 3 - Fluid Slippage - High Pressure Case
1765 psi plunger differential pressure
Lab data compared to field data

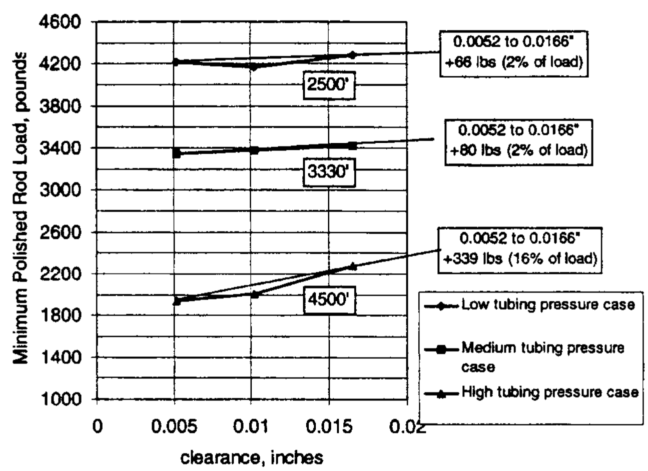

Figure 4 - MPRL vs. Clearance
Backpressure used to simulate deeper wells

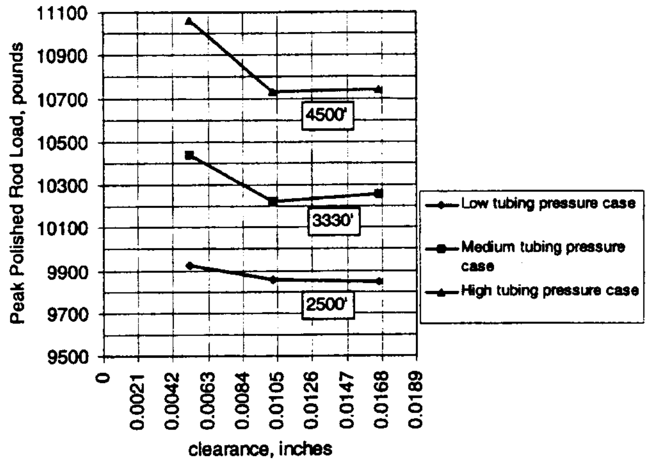

Figure 5 - PPRL vs. Clearance
Backpressure used to simulate deeper wells

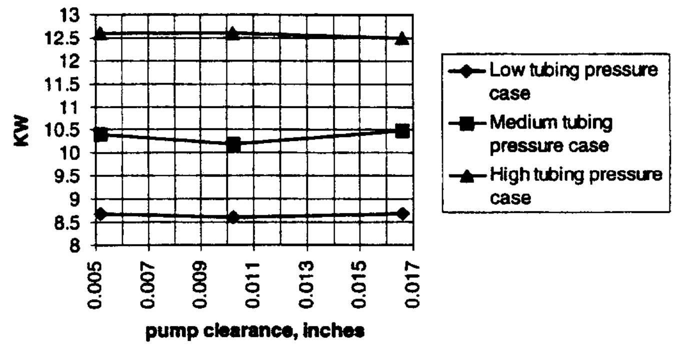

Figure 6 - Nabla KW Measurements vs. Clearance

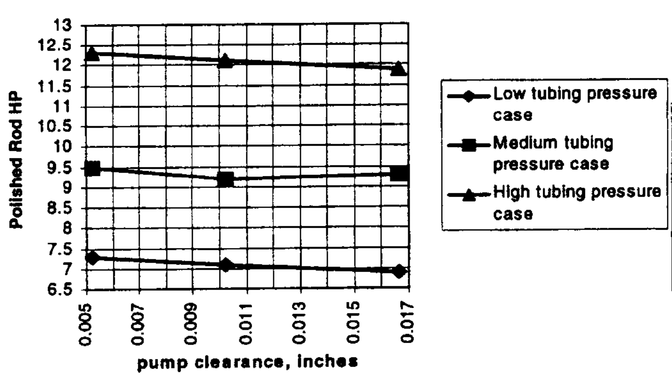

Figure 7 - Polished Rod Horsepower vs. Clearance

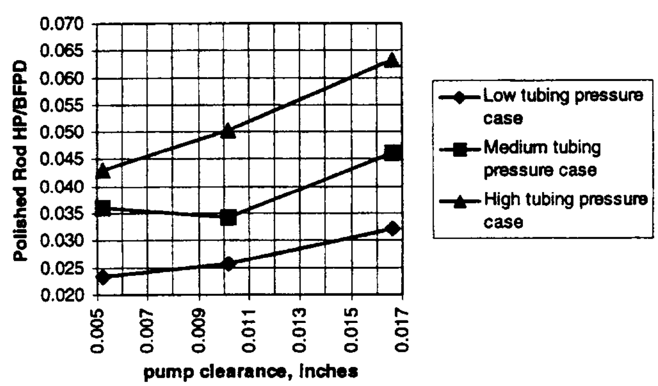

Figure 8 - Polished Rod Horsepower/BFPD vs. Clearance

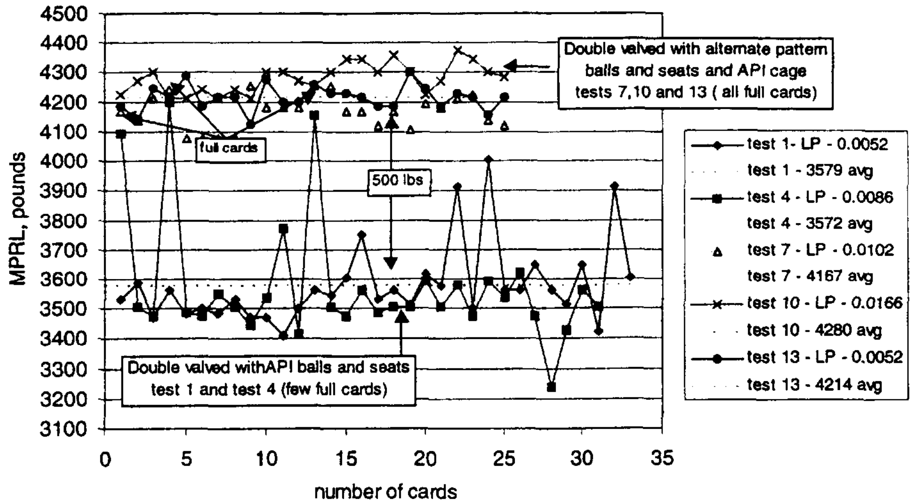

Figure 9 - MPRL for Low Tubing Pressure Cases
40 psi approximately 2500'

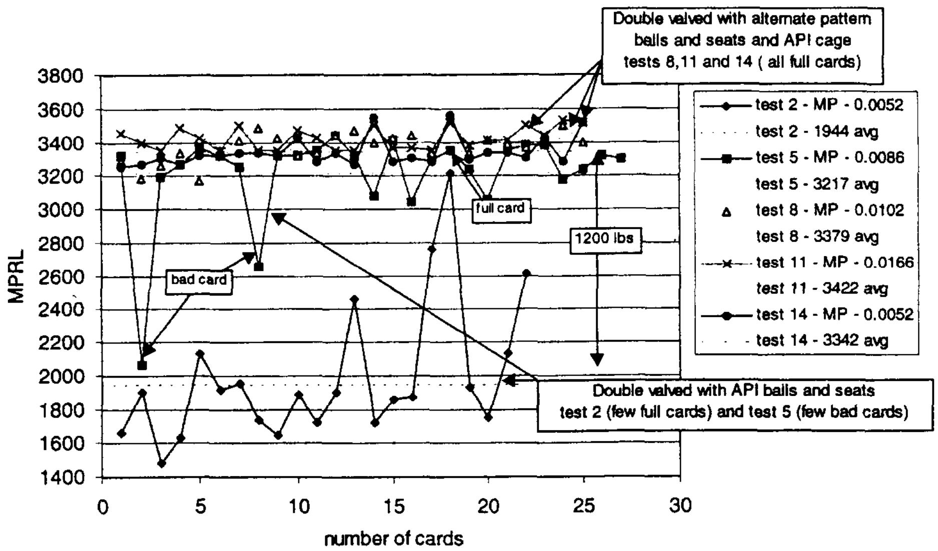

Figure 10 - MPRL for Medium Tubing Pressure Cases
400 psi approximately 3330'

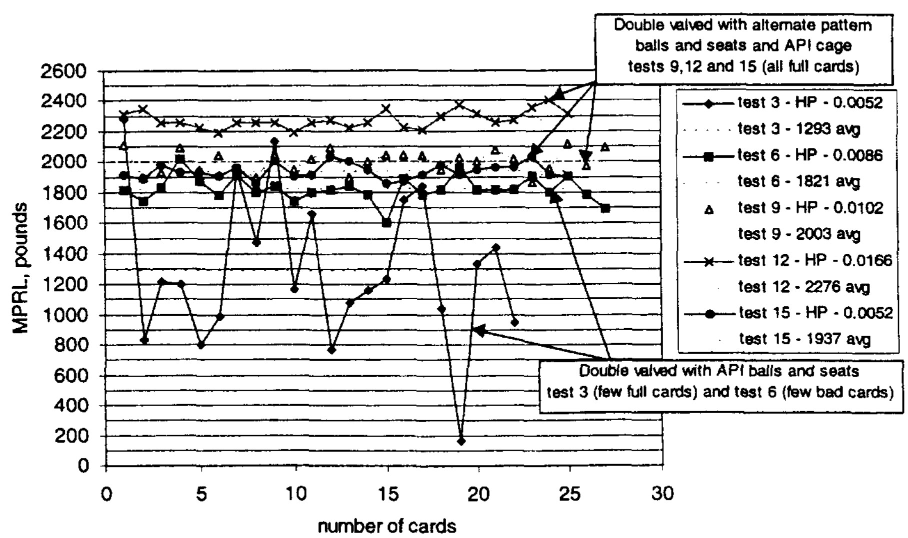

Figure 11 - MPRL for High Tubing Pressure Cases
900 psi approximately 4500'

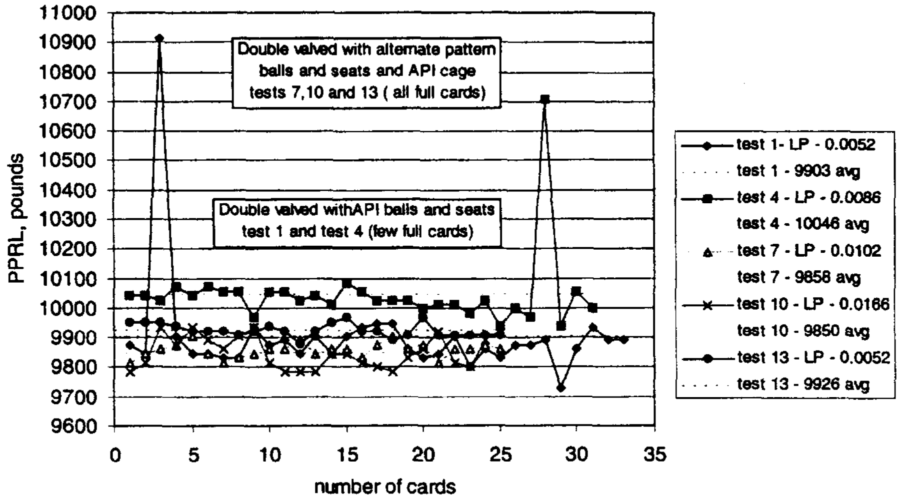

Figure 12 - PPRL for Low Tubing Pressure Cases
40 psi approximately 2500'

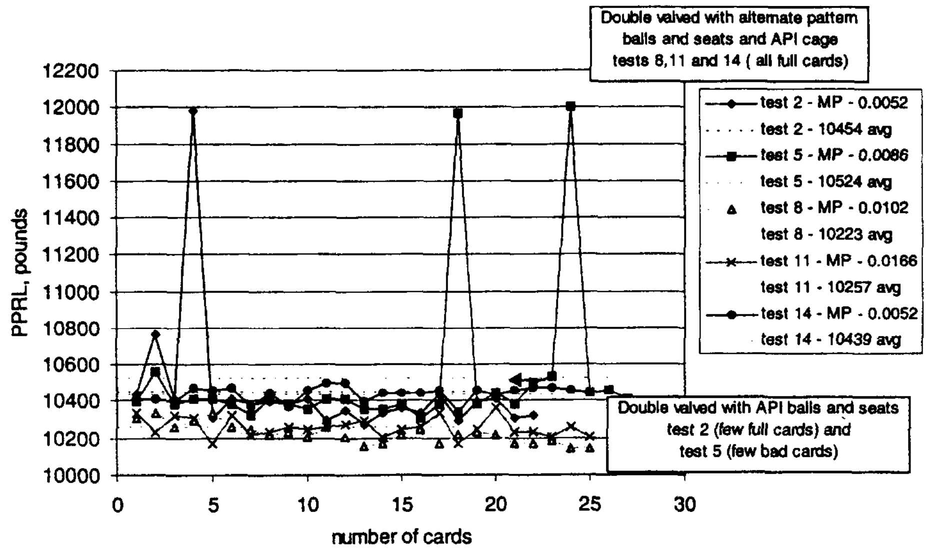

Figure 13 - PPRL for Medium Tubing Pressure Cases
400 psi approximately 3330'

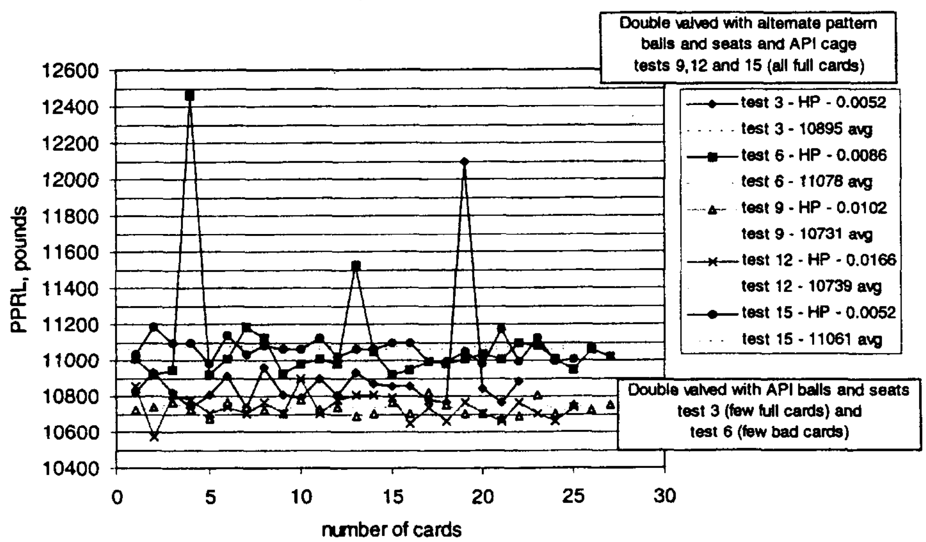

Figure 14 - PPRL for High Tubing Pressure Cases
900 psi approximately 4500'