EQUIVALENT GAS FREE PUMP FILLAGE LINE

O. Lynn Rowlan, Echometer Company
James N. McCoy, Echometer Company
Carrie Anne Taylor, Echometer Company
Russell Brown, Wells Whisper

ABSTRACT

A new term "Equivalent Gas Free Pump Fillage Line" represents the amount of liquid fillage inside the pump chamber when the traveling valve opens during the down stroke. Adjustments for gas in solution, slippage, free gas, and compressibility of liquid due to pressure and temperature are required to determine the amount of stock tank liquid produced per day for a selected stroke.

Field dynamometer data from eight different wells will be used to compare calculated to measured surface oil and water production volumes. The equivalent gas free pump fillage line will be shown for each well's representative pump card.

The pump card calculated gas produced up the tubing and the acoustic fluid level tested free gas produced up the tubing/casing annulus are used to determine system gas separation efficiency. This enhanced analysis technique allows answering many complicated questions concerning oil, water, and gas production with respect to the downhole pump card.

Introduction

The Equivalent Gas Free Pump Fillage Line represents the amount of liquid filling the pump chamber when the traveling valve, TV, opens during the downstroke portion of the sucker rod pumping cycle. Oil, water, and gas enter the pump chamber through the open standing valve, SV, during the up stroke. Oil, water and gas discharge into the tubing through the open TV during the down stroke. On the down stroke the sucker rod pump plunger compresses the fluids inside the pump chamber, increasing the chamber pressure from the intake pressure at the top of the stroke to the discharge pressure at the point when the TV opens. The effective plunger travel, EPT, is the pump stroke where the TV opens. The shape of the pump card during the compression portion of the pump cycle is due to the increasing chamber pressure reducing the free gas volume inside the pump chamber. The difference between the EPT and gas free pump fillage line represent the amount of compressed free gas inside the pump chamber when the TV opens. Determining the amount of stock tank liquid contained in a selected pump stroke requires the use of enhanced analysis techniques.

The maximum plunger travel, MPT, is the gross volume swept by the pump plunger. The gross pump displacement must be adjusted to determine the liquid volume discharged from the pump. Adjustments for free gas filling the pump chamber must be determined. Reduction in gross pump displacement includes the impact from tubing movement, delayed closing of valves, and slippage through the pump clearances. Surface stock tank volumes include adjustments to oil volume in the pump for gas in solution at the intake pressure, plus adjusting oil and water volumes for compressibility due to pressure and temperature change.

Field dynamometer data acquired using a calibrated horseshoe load cell on eight different wells will be used to calculate pump liquid converted to stock tank. Then the converted stock tank volumes will be compared to measured surface oil and water production volumes. A gas free pump fillage line will be shown for each well based on the shape of the gas compression curve during the down stroke.

Gas produced up the tubing is determined from the pump card calculations and free gas produced up the tubing/casing annulus is determined from the analysis of the acoustic fluid level test acquired on the well. The system gas separation efficiency is determined by comparing the gas produced up the casing to the total gas produced up both the tubing and casing annulus.

The first step of the enhanced analysis process is to input the correct information describing the existing wellbore and artificial lift system configuration. Accurate and representative oil and water production rates are used to determine the percent oil. Oil, water, and gas compressibility correlations in combination with fluid gravities determine the compression behavior of the fluids inside the pump chamber during the down stroke.

Tubing pressure, tubing fluid gradient and deviation survey are required to determine the pump discharge pressure. The pump discharge pressure is impacted by the amount of free gas produced up the tubing. The tubing fluid gradient can be determined using the Ross-Gray multiphase flow correlation. The amount of liquid and gas discharged into the tubing from the pump stroke, along with the percent oil is used by the multiphase flow correlation. Pump discharge pressure and weight of rods in fluid depend on the tubing fluid gradient including adjustment from the amount of gas pumped up the tubing. Tubing fluid gradients are lightened when gas is discharged into the tubing and tubing fluid gradient representative of actual conditions will aid in trouble shooting sucker rod lift problems.

Why is the tested Stock Tank production at the surface different than the EPT displacement?

A common question is: "Why is the tested Stock Tank production at the surface different than the EPT calculated pump displacement". Determining the amount of stock tank liquid contained in one pump stroke requires the use of enhanced analysis techniques. The analysis technique described in this paper uses the "Equivalent Gas Free Pump Fillage Line" to represent the amount of liquid filling the pump chamber when the traveling valve opens during the downstroke portion of the sucker rod pumping cycle. The enhanced technique allows answering many of the complicated questions concerning oil, water, and gas production with respect to both maximum and effective plunger travel.

Additional detailed information describing the existing wellbore and artificial lift system configuration must be provided and used in the calculations. Accurate and representative oil and water production rates are used to determine the percent oil, if not entered the percent oil is defaulted at 10 percent. Oil, water, and gas compressibility correlations in combination with fluid gravities determine the compression behavior of the fluids inside the pump chamber during the down stroke. Tubing pressure, tubing fluid gradient, and deviation survey are required to determine the pump discharge pressure. The pump clearance, fluid viscosities, and plunger size is required to accurately determine any losses in production due to slippage using the Patterson Slippage Equation.

The Compression Process

During the upstroke, the standing valve (intake valve) is open, the traveling valve is closed, and well fluids are filling the pump chamber at/near the pump intake pressure. At the top of the stroke, the standing valve ball seats and the compression portion of the pump cycle begins. Both the standing valve and the traveling valve balls are on the seat at the top of the stroke. The transfer of the fluid load from the rods to the tubing occurs during the compression portion of the pump cycle. As the plunger moves down, the pressure inside the pump chamber increases as the volume of fluid (oil, water and gas) inside the pump chamber decreases. Once the pressure inside the pump chamber exceeds the discharge pressure on top of the traveling valve, the traveling valve ball comes off seat and the fluids discharge into the tubing.

1. A stroke representative of normal operations for the well is selected from dynamometer measurements.
2. Percent oil is determined from oil and water production rate or defaulted to 10%.
    a. Percent oil is needed to calculate fluid properties from correlations, plus the amount of oil and water inside the pump chamber.
3. Accurate well data must be entered into the diagnostic software.
    - Rod String description, deviation survey, plunger length, diameter, and clearances
    - Bottom hole temperature, oil gravity, gas gravity, and water gravity are used to calculate the fluid properties inside the pump chamber at the intake pressure and discharge pressure.
    - Downhole conditions of intake pressure, discharge pressure and temperature at the pump are used to calculate liquid in the pump, free gas in the pump, and also the compressibility of the gas.

Visual analysis of a downhole pump card identifies the beginning point at the top of the stroke, and follows the compression curve during the downstroke to the point where the traveling valve opens. The shape of the compression curve, along with the calculated intake pressure and discharge pressure allow determination of the amount of free gas that entered the pump during the upstroke when the standing valve was open, and also the amount of liquid inside the pump when the traveling valve opens during the downstroke.

At the top of the stroke, when the standing valve is open, the pressure inside the pump chamber is equal to the intake pressure. In order for the fluid in the pump chamber to discharge into the tubing, the intake pressure inside the pump chamber must be raised to the discharge pressure which is holding the traveling valve ball on the seat. The technique used to determine the discharge pressure takes the tubing fluid gradient, the true vertical depth of the well to the pump, and the known tubing pressure, and applies them to the following equation:

Pdis (TV opens) = Tubing Fluid Gradient x TVD (to the pump) + Tubing Pressure (1)

Three assumptions are made for simplifications for the calculations regarding the compression of gas inside the pump chamber during the downstroke:

1. Gas in solution in the oil is determined at the pump intake pressure
2. No free gas goes in solution into the during the compression cycle.
3. Temperature inside the pump chamber remains constant.

Inside the pump chamber on the downstroke, the compression cycle happens quickly. Free gas is present inside the pump chamber, but the sudden compression of fluids allows enough time for very little gas to go into solution. A Tulsa University[2] study has shown that in general 8 to 15 seconds of oil/gas contact at high pressure is required for free gas to go into solution within a vigorously mixed container. However, in a sucker rod pump chamber due to gravity acting on the relative fluid densities the free gas volume is not in contact with the oil; the water, oil, and gas are segregating inside the pump chamber. The compression cycle may last only 1 or 2 seconds, so very little gas has time to go into solution in the oil during the compression cycle. Thus a simplifying assumption is made in the calculation that no free gas goes in solution into the oil during the compression cycle on the downstroke.

Generally, when gas is compressed, pressure and temperature increase. However, the pump is downhole in the earth at the depth of the reservoir and is surrounded by a constant temperature. It is assumed that any increase in temperature is absorbed and dissipated by the surrounding earth heat sink and liquids inside the pump chamber, therefore the temperature of the fluids in the pump chamber is assumed to remain constant at the reservoir temperature at the pump depth.

Intake conditions:

- At top of stroke, MPT, standing valve closes and traveling valve is closed to create the compression chamber.
- Gas volume fills all or a portion of the pump chamber.
- Gas volume and liquids inside the pump chamber are at the intake pressure.

Discharge conditions:

- Exists at the EPT point during the downstroke where the traveling valve opens.
- Gas volume has been compressed to a smaller volume.
- Gas volume and liquids are discharged into the tubing at the discharge pressure.

The calculations use the standing valve close and traveling valve open plunger position during a pump cycle to identify the beginning and end of the compression cycle. The software algorithms automatically select the standing valve close position point and the traveling valve open position point during the pumping cycle. If the standing valve close and traveling valve open points are not selected properly, the calculations will be erroneous. Therefore, an option is provided to allow the operator to manually adjust the valve open and close points to the proper positions at the corners of the pump card so that the compression cycle is correctly identified.

Tubing Fluid Gradient

The tubing fluid gradient is used in the determination of the pump discharge pressure and the fluid buoyancy force acting on the rod string. Each rod string size and type has a known weight in air and total length, therefore the weight of the rods suspended in air can be determined. The rod string is installed within the tubing, which is filled with fluid having a certain gradient. The weight of the rod string buoyed in the tubing fluid is lighter than the weight of the rod string in air. This buoyancy force is considered in the calculation of the weight of the rods in fluid. The well bore deviation survey is used to determine the vertical weight of rods in fluid. The weight of the rods in fluid is equal to the weight of the rods in air minus the buoyancy of the fluid. The gradient of the tubing fluid can be determined in several different ways.

1. One method is to calculate the flowing gradient using a multi-phase flow correlation once the amount of oil, water, and gas discharged into the tubing has been determined. This is an iterative process because the pump discharge pressure impacts the calculated free gas volume inside the pump chamber. The pressure gradient from the surface to the pump discharge includes the effects of the well bore deviation. The multi-phase flow correlation is used to calculate the pump discharge pressure by starting at the surface tubing pressure and calculating pressure change due to the flow of fluids through each section of unique tubing internal diameter and sucker rod outside diameter down to the pump discharge. The change in multi-phase flow pressure versus depth is used to determine the tubing fluid gradient.

2. When little to no gas is produced in the well, the gas free tubing fluid gradient can be calculated based on percent oil, oil gravity and water gravity. In most sucker rod pumped wells having low pump intake pressure the gas free tubing fluid gradient has been found to be very accurate in determining the weight of rods in fluid and the pump discharge pressure. However when the pump intake pressure increases and large quantities of free gas discharge into the tubing, then the gradient will generally become lighter unless high fluid flow rates increase the pressure drop resulting from fluid friction. This simple gas free tubing fluid gradient calculation method does not consider the impact from additional variables such as gas, pressure, temperature, deviation and other parameters. For most sucker rod lifted wells the gas free tubing fluid gradient is usually the best default tubing fluid gradient calculation method.
3. The tubing fluid gradient can be calculated from a load cell measured weight of rods in fluid through the use of the SV test. During dynamometer measurements, a SV Test can be performed by bringing the pumping unit to a smooth and complete stop near the bottom of the downstroke. When the pumping unit is gently stopped on the downstroke and all pressure in the tubing remains applied to the closed SV, then the fluid load applied by the pump to the rods is released due to no differential pressure acting across the TV. Barring errors in rod load measurement from impacts such as stuffing box friction, paraffin or wellbore deviation, the weight of the rod buoyed in tubing fluid is measured. The buoyancy force acting on the rod string is equal to the difference between the weight of rods in air known to be ran in the well and the SV test measured weight of rods in fluid. Determining the volume of rods installed in the well along with the buoyancy force allows the calculation of the SV Test tubing fluid gradient. The SV Test tubing fluid gradient is often the least accurate because the error in the SV load measurement can be large in comparison to the buoyancy force acting on the rod string.
4. The user entered tubing fluid gradient can be estimated based on a visual inspection of the downhole pump card position with respect to the Zero Load line. During the downstroke when the TV is open the pump card loads should be positioned on the Zero Load line, assuming no abnormal forces exist impacting pump card loads. Unaccounted effects from gas flowing up the tubing or missing/unknown oil and water rates or gravities will result in incorrect tubing fluid gradients determined from any of the previously discussed methods. The tubing fluid gradient can be manually adjusted by visual inspection to position the pump card with respect to the Zero Load line.

The calculated pump discharge pressure depends on the tubing fluid gradient, true vertical depth, and tubing pressure. The discharge pressure is calculated by multiplying the tubing fluid gradient times the true vertical depth and adding the tubing pressure. The TV is assumed to open at the EPT line because the fluids inside the pump chamber were compressed from the intake pressure to the calculated pump discharge pressure.

During the upstroke, when the Standing Valve is open, the pump chamber pressure is assumed be equal to the pressure on the outside of the pump, the intake pressure. The pump chamber pressure equal to the pump intake pressure is reasonable, when fluid viscosity is low and pressure drop across the open standing valve is small. The pressure drop through the open SV is usually not significant unless the fluids are viscous or flow into the pump intake is restricted. The pump intake pressure at the top of the pump stroke when the SV ball goes on seat is determined by subtracting the differential pressure acting across the pump plunger during the up stroke away from the pump discharge pressure. The differential pressure acting across the pump is the discharge pressure minus the intake pressure, which is equal to the fluid load, Fo, divided by the pump plunger area. The height of the pump card, Fo, is used to determine the amount of compression applied to the well fluids inside the pump chamber. Intake pressure can also be calculated from the following equation:

PIP = Tubing Pressure + Pump Depth (TVD) * Fluid Gradient – Fo/Plunger Area (2)

The fluid inside the pump chamber is compressed by a pressure equal to the differential pressure represented by the height of the pump card, Fo divided by the plunger area. The intake pressure at MPT is compressed to the pump discharge pressure at EPT by an amount of pressure equal to the differential pressure acting across the pump plunger.

Pump Card Analysis of Pump Displacement

In the following example, the EPT pump displacement determined from the dynamometer test is equal to 74 barrels per day production. Surface stock tank measurement was equal to 59 stock tank barrels per day, STBPD (**Fig. 1**). A common question is why does the measures stock tank production not match the EPT pump displacement? The pump displacement can be much larger than the liquid volume produced into the stock tank. When production does not match the operator often questions what is happening to the liquid that is not getting to surface, is there a possible problem or a leak. There are a few additional factors impacting the pump displacement calculation that could be causing the difference.

1) Free gas exists inside the pump when the traveling valve opens.
2) Slippage occurs between the plunger and the barrel.
3) Temperature and pressure at the pump impact both the oil and water volume when compared to the oil and water volume in the stock tank at standard pressure and temperature.
4) The tubing may be unanchored or partially unanchored.
5) There may be a delay in the TV closing.
6) There could be gas in solution swelling the oil volume.

The shape of the compression curve, illustrated in **Fig. 2** represents the compression of the gas inside the pump chamber from the intake pressure at MPT at the top of stroke to the discharge pressure at EPT during the downstroke when the TV opens. The amount of liquid in the pump chamber, the intake pressure and the discharge pressure control the shape of the compression curve. When the pump card is analyzed the following observations/assumptions can be made:

- A certain amount of gas enters the pump chamber.
- A certain amount of liquid enters the pump chamber.
- Slippage increases the liquid volume in the pump chamber.
- The liquid volume in pump chamber can be assumed to be a fixed height and remains constant during the compression portion of the pump stroke.

The ratio of gas volume at intake pressure divided by the compressed gas volume at discharge pressure represents the compression ratio for a particular stroke. (**Fig. 3**) Pressure is raised from 242 psi at intake to 2587 psi at discharge, yielding a compression ratio of 15.8. As long as the unswept volume of the pump chamber is liquid filled, then the compression ratio is always high enough to open the traveling valve during the stroke. At the 77.4 inches of MPT stroke 79 BPD of free gas enters the pump filling 41.4 inches of the pump chamber. At the 38.8 inch EPT when the TV opens 79 BPD free gas has been compressed to 5 BPD filling to 2.77 inches of the pump chamber. **Eq. 3** Boyles Law includes the adjustments due to hydrocarbon gas compressibility (Z factor). **Eq. 3** can be used to calculate the relationship between the gas volume when the SV closes inside the pump chamber at MPT compared to the gas volume at EPT inside the pump chamber at discharge pressure when the TV opens. (**Fig. 4**). **Eq. 3** is used to calculate the 38.6 inch Equivalent Gas Free Pump Fillage Line.

$$\frac{PV}{Z}, \text{Intake} = \frac{PV}{Z}, \text{Discharge} \qquad (3)$$

The relationship shown by **Eq. 3** is reasonably accurate and represents what happens inside the pump chamber during compression of the free gas. The Z factor at intake and discharge pressure is determined using the gas gravity, pressure and temperature. The intake pressure, P intake, relates to EPT when the TV opens and discharge pressure, P discharge, relate to the MPT when the SV closes. The Equivalent Gas Free Pump Fillage Line represents a volume of liquid, L, inside the pump chamber during the stroke. (MPT-L) times plunger area represents the free gas volume inside the pump chamber at intake pressure. (EPT-L) times plunger area represents the free gas inside the pump chamber at discharge pressure. L or the Equivalent Gas Free Pump Fillage Line is determined when **Eq. 3** is solved.

(**Fig. 4**) A vertical line drawn on the pump card at the point when the traveling valve opens reflects the distance of the effective plunger travel (EPT). A second dotted line at 38.6 inches represents the maximum plunger travel (MPT) minus the effective plunger travel (EPT). The small area between the EPT and Equivalent Gas Free Pump Fillage Line represents the compressed gas volume in the pump chamber at the discharge pressure. If the assumptions that no gas goes into solution, the temperature inside the pump remains relatively constant, and that the liquid volume remains constant during the downstroke then calculations based on **Eq. 3** are generally representative of what happens during the compression portion of the pump cycle. Essentially, at discharge, a calculated volume of gas and a calculated volume of liquid exist in the pump chamber.

In addition to pump displacement losses due to free gas in the pump, liquid slipping between the plunger and the barrel must be accounted for in the adjusted pump displacement. Research done at Texas Tech University to develop the Patterson Slippage Equation, **Eq. 4**, which is used to calculate the volume of slippage during a stroke if the pump clearance, fluid viscosities, pumping speed, and plunger length and diameter are known. Slippage occurs when the traveling valve ball is on the seat during the upstroke. Differential pressure acting across the plunger pushes typically water through the clearances between the plunger and the barrel into the pump chamber. The Patterson Slippage Equation, **Eq. 4**, is used to calculate the amount of fluid slipping past the pump.

$$\text{BPD, slip} = \left[\left(0.14 \cdot SPM\right) + 1\right] 453 \frac{DPC^{1.52}}{L\mu} \qquad (4)$$

Calculated slippage is then subtracted from the effective plunger stroke along with the subtraction for losses due to free gas in the pump at discharge and any losses due to traveling valve closure delays. The length and diameter of the plunger are used along with the well depth, tubing discharge pressure, plunger clearance, fluid load, and tubing fluid gradient to calculate the differential pressure acting across the plunger. Once the differential pressure is determined, the amount of slippage is calculated using the Patterson Slippage Equation.

Field Dynamometer Example Data

Field dynamometer data acquired using a calibrated horseshoe load cell on eight different wells will be used to compare the calculated to the measured surface oil and water production volumes. A gas free pump fillage line will be shown for each well based on the shape of the gas compression curve during the downstroke. The dynamometer card calculated pump displacement in terms of stock tank barrels will be compared to measured barrels at the surface. Each well will show a different idea or concept and how corrections made for gas in solution, temperature, slippage and free gas inside the pump can be used to determine a representative pump displacement volume in terms of comparing stock tank barrels per day calculated from the pump card to stock tank barrels measured at the surface.

Example 1

Pump card analysis begins with examining the load lines on the upstroke and the load on the downstroke as shown in **Fig. 5**. A flat load line on the upstroke, from the point where the standing valve opens to where the standing valve closes, indicates the differential pressure acting across the pump plunger is fairly constant and the full fluid load is applied to the rod string during the upstroke. A flat load line near zero load from the TV open point to the TV close point, means the TV is open with essentially no load is acting on the rod string from the pump plunger on the downstroke, The pump card load lines are used to determine pump intake and discharge pressures. The pressures are used in the valve open and close calculations. Proper positioning of the valve open and close points are essential for pump fillage analysis.

The first step to determine the Equivalent Gas Free Pump Fillage line is to choose the most representative stroke for a well's normal operating conditions. **Fig. 6** for Well A overlays all strokes acquired during a dynamometer test. The Average EPT for Well A for this dataset is 37.77 inches. Therefore, a pump card having a e EPT close to the average should be selected for analysis. For this analysis, stroke 104 with a SPM of 4.136 and an EPT of 37.8 inches is selected.

The next step is to verify load lines from the pump card used to calculate the Equivalent Gas Free Pump Fillage Line (**Fig. 6**) match reasonably well with the reference load lines. There are several identifying factors to consider when determining the correct placement:

- The load on the upstroke should match the calculated load reference line determined by the fluid level shot.
- The bottom of the pump card should be positioned on the zero load line where the friction is released.
- Verify the tubing fluid gradient is representative. On this dataset, a user entered tubing fluid gradient of 0.32 psi/ft is used to match the pump loads with reference load lines.
- The pump intake pressure (PIP) on the pump card is 184.5 psi which compares to the 200 psi PIP calculated from the fluid level measurement.

The Pump Card Analysis for Well A (**Fig. 7**) as previously discussed uses the intake pressure, the discharge pressure to calculate amount of liquid in the pump chamber as represented by the Equivalent Gas Free Pump Fillage Line at 37.8 inches. The amount of liquid in the pump chamber is used to solve for the amount of free gas in the pump. In this case, 41.73 inches of free gas exist at the intake and 2.10 inches of free gas are present in the pump at discharge, indicating the gas volume was compressed from 41.73 inches at intake to 2.10 inches at discharge. During the upstroke, the pumped filled with 41.73 inches of gas at the intake, resulting in a loss of 80 barrels of pump displacement due to free gas entering the pump through the open SV. To open the traveling valve, the plunger must move down the equivalent pump stroke of 41.73 inches to open the traveling valve and increase pressure inside the pump chamber to the discharge pressure. The total pump stroke of 77.43 inches minus 41.7 inches is the Effective Plunger Travel (EPT). When the valve opens, 2.10 inches of free gas remains at the discharge pressure inside the pump. Another adjustment of 5.72 inches was made to reduce pump displacement due to pump slippage through the 0.003 inch clearances in the 60 inch long plunger 2 inch diameter pump. Considering the losses due to free gas existing inside the pump, pump stroke lost to the compression of gas, and stroke loss due to calculated slippage, the adjusted pump stroke length, SL, for Well A is 29.99 inches.

$$PumpDisplacement = 0.1166 \times SPM \times SL \times D^2 \qquad (6)$$

Using the 29.99 inch adjusted SL, 4.136 SPM, and 2 inch diameter, D, plunger Eq. 6 is used to calculate the 58 BPD of liquid is discharged from the pump into the tubing. The oil has 1772.0 scf of gas dissolved in solution in the oil. As the oil flow to the surface the pressure and temperature drop and the dissolved gas comes out of solution. At the surface standard pressure and temperature the oil volume is reduced to 53 STBPD. Gas produced up the tubing from the pump card analysis is equal to 6.7 Mscf/D compared to 9.1 Mscf/D of gas flow up the annulus from the fluid level measurement. Thus a total of 15.9 Mscf/D of gas is produced based on the pump card analysis and fluid level analysis, yielding a total system gas separation efficiency of 57.6%. The calculated 15.9 Mscf/D compares reasonably well to the measured gas production rate of 22.0 Mscf/D.

Example 2

Fig. 8 displays the dynamometer measurement for Well B. Well B exhibits a high fluid level and fairly high pump intake pressure of 797 psi. The pump is full of liquid and produces 60 BWPD and 300 BOPD at 7.347 SPM. Stroke 183 is the representative stroke for the pump card analysis seen in **Fig. 9**. The pump card measurements calculate a pump intake pressure of 833.4 psi which is slightly higher but comparable to the PIP from the fluid level of 797 psi. The maximum plunger travel is 143.4 inches and 5.86 inches of free gas exist in the pump. The Effective Plunger Stroke is 139.95 inches, equivalent to a pump displacement of 607 BPD. Free Gas at Discharge is about 2.3 inches or 10 BPD. A total of 2.32 inches of free gas remain in the pump when the discharge valve opens. A slight TV close delay is visible on the card. The Patterson Slippage Equation calculates 1.66 inches of slippage which equates to only 7 BPD due to the low differential pressure between the 800 psi pump intake pressure and the 1900 psi discharge pressure. The total calculated stock tank fluid at the surface is 580 bb/d, but the stock tank measurement is 603 BPD. The pump is completely full of liquid, but the rounded shape of the pump card at the top of stroke resulted is calculating free gas in the pump, resulting in an error in volume of approximately 23 BPD.

Example 3

Selecting the representative stroke is important. When measured pump cards acquired during one session range from displaying a full pump to partial liquid fillage, representative stroke selection will greatly impact the calculation. Consider the pump card analysis for Well C represented in **Fig. 10**. Well C is currently being run on hand. Stroke number 197 was initially selected for the analysis. The calculated pump displacement using stroke 197 was 98 BPD. However, production at the surface was measured to be only 16 STBPD. Notice how the pump fillage changes for Well C in **Fig. 11**. Consider the conditions under which the dynamometer measurements were taken. If a well is shut down for a period of time for test equipment set up, the well should be given at least that same amount of time to stabilize to normal pumping conditions after restarting the well. Consideration should also be given to the conditions of the well when production measurements were taken. Only then can the most representative stroke be selected. A second stroke was selected for the analysis on Well C that better represented the measured production at the surface. Analysis of stroke 2 shows 29 inches of effective plunger travel, and an Equivalent Gas Free Pump Fillage Line of 22.45 inches. The Pump Card Analysis shown in **Fig. 12** indicates 160 inches of stroke lost to free gas, equivalent to 199 BPD, entering the pump. The equivalent of 16 B{D, or 9.78 inches, is lost due to slippage, and 6.63 inches is lost to free gas in the pump when he TV opens. Of the 30 inches of overall effective plunger travel, over half of EPT is lost due to slippage and free gas when the TV opens.

Example 4

The tubing fluid gradient is critical in determining the gas volume at the pump intake pressure. The pump card analysis of Well D (**Fig. 13**) illustrates the position of the pump card with respect to the reference load lines. The top of the pump card is positioned below the maximum fluid load line, FoMax, which under normal conditions indicates a high fluid level, the high PIP of 1425 psi would be expected. However, the shape of the card suggests fluid pound conditions exist, and the positioning of the card with respect to the reference load lines indicates a possible problem with the calculations. The fluid level measurement of Well D shows the fluid level to be just above the pump, and the calculated PIP from the fluid level is a low 95 psi. Stroke 9 is selected as representative for this well, and the input data from the well file is reviewed for accuracy to help determine the differences between the dynamometer and fluid level measurements. No production data had been entered on this well. Production data is essential to correctly determine the tubing fluid gradient used in the PIP calculation. Failure to enter required data forces the software to use defaults and to make assumptions when performing calculations. In this case, since no production data had been entered, the software used a default tubing fluid gradient of 0.455 psi/ft. The positioning of this fluid pound pump above the zero load line and below the FoMax line signifies the weight of rods in fluid is too light. When the correct weight of the rods in fluid is used in the wave equation, the pump card should sit on the zero load line with the pump card load on the up stroke matching the calculated load from the fluid level shot (Fo from Fluid Level). The fact that is card is improperly positioned indicates the default tubing fluid gradient is too high. The tubing fluid gradient can be adjusted by using one of four methods of calculations:

1) Gas free gradient based on oil and water production measurements,
2) Gradient from the measured weight of rods in fluid,
3) Multiphase flow gradient due to liquid and gas in the pump flowing up the tubing,
4) Or by user entered adjustments.

Fig. 14 shows the effects of manually adjusting the tubing fluid gradient to better match the reference load lines. The third adjustment on the figure uses a tubing fluid gradient of 0.29 psi/ft to best match the top of the pump card to the Fo from Fluid Level load line. The bottom of the card is now positioned slightly below the zero load line which may be explained by unaccounted friction, by verifying the vertical rod length data is correct, or perhaps a well deviation survey needs to be entered into the well file. **Fig. 15** shows the corrected pump card when the proper tubing fluid gradient is used for the calculation. The corrected PIP of 51.5 psi now better compares to the PIP from the fluid level calculation of 95 psi.

Example 5

High pressure gas present at the pump intake greatly reduces pump fillage and results in a greater loss in pump displacement than expected. Well E (**Fig. 16**) has a high intake pressure of 1618 psi with a 2959 psi discharge pressure. To open the TV compression needs to double the pump intake pressure to be greater than the discharge pressure. The plunger only needs to move a short distance in this well to double the pressure and open the valve. The distance seems small by visual inspection, but the pump card analysis calculates 10 inches of gas compression, and 11.4 inches of free gas in the pump when the valve opens. A significant amount of gas is in solution in the oil due to the high intake pressure. The effective stroke is 588 BPD of pump displacement. When losses for free gas (19.45 inches = 71 bbl/d), and slippage (2.38 inches = 9 BPD) are accounted for, the pump displacement drops to 544 bbl/d. Considerations for the 16.18 Mscf/D gas in solution and temperature effects drop the pump displacement an additional 110 BPD for a total calculated pump displacement of 434 BPD. The total gas up the tubing is 199.7 Mscf/D. The fluid level shot shows that there is no casing pressure buildup, therefore all of the produced gas is being pumped up the tubing.

Example 6

A delay in traveling valve closing effects the total pump displacement and must be accounted for in the analysis. **Fig. 17** illustrates how gas interference changes over a 30 minute time interval. Well F dynamometer measurement captured 408 strokes. Stroke 243 is used as the representative stroke on this well. Well F displays gas interference throughout the dynamometer measurement, reflected by the partial pump fillage pump cards. The top of the card reaches the FoMax line, indicating a low pump intake pressure with a low rate of free gas entering the pump and consuming a large volume of pump displacement. Further analysis of the cards also suggest a TV delay on the upstroke of 2.01 inches, equal to a loss in production of 5 BPD. This loss in production must be accounted for in the pump displacement calculation shown in **Fig. 18**. The pump card analysis in **Fig. 19** calculates 18.77 inches of free gas in the pump at the MPT, meaning a loss of 47 BPD of pump displacement due to a low rate of gas entering the pump consuming a large portion of the pump displacement. At discharge, only .14 inches of free gas is present when the TV opens. The effective plunger stroke is 43.59 inches, equating to 168 BPD, but additional adjustments must be made of 2.01 inches for the delayed close of the TV and 5.29 inches lost to slippage. The adjusted calculated production is 88 BPD compares to the measured 76 BPD.

Example 7

The concept of selecting the most representative stroke provides an accurate analysis of the normal operating conditions of a well. **Fig. 20** shows the dynamometer surface and pump card for stroke 13 initially used for calculations on Well G. The production on Well G from the chosen pump card is calculated as 56 BPD. The measured production on Well G is 20 BPD. A review of the stroke overlay (**Fig. 21**) reveals several identifying factors to aid in proper selection of the representative stroke. The most incomplete strokes have an effective stroke length of between 53-55 inches. Stroke number 73 is next selected as the representative stroke, but the pump card analysis calculates 55 BPD pump displacement which is still high compared to the measured production of 20 BPD. A review of the well file information for Well G reveals this well is on 12 hour run time. In order to make the calculated production rate more accurate, the pump card analysis must be adjusted for run time. **Fig. 22** shows the calculated pump displacement is 28 BPD with the production rate adjustment, which is much closer to the measured 20 BPD.

Example 8

Example 8 is an example of a slippage calculation on a well. The barrels of liquid lost to slippage can be equated to inches of reduced downhole stroke. In this example, 11.1 BPD of slippage results in 5.6 inches of reduced downhole stroke. The calculated slippage is used in the pump card analysis (**Fig. 23**) and is subtracted from the effective plunger stroke along with the loss of 2.77 inches for free gas in the pump at discharge. The total pump displacement is 30.39 inches which converts to 58 BPD of pump displacement. **Fig. 23** shows the adjustment of 58 BPD pump discharge to 53 BPD at surface stock tank conditions, which has been adjusted for both gas in solution and temperature. The calculated stock tank barrels of oil is comparable to the production data for this well.

Conclusion

The differences between the liquid in the stock tank and the typical the pump displacement determined using the effective plunger travel can be explained utilizing the Equivalent Gas Free Pump Fillage Line, plus other adjustments to the fluids inside the pump chamber. Correctly locating the traveling and standing valve open and close points on the pump card are critical to the Equivalent Gas Free Pump Fillage Line location. The difference between the maximum plunger travel and the equivalent gas free pump fillage represents the amount of the pump displacement consumed by free gas entering the pump chamber during the upstroke. Knowing the amount of gas being pumped into the tubing can be used to better understand the efficiency and performance of the downhole gas separator.

Accurate artificial lift equipment description, pumping speed, deviation survey, fluid properties, tubing fluid gradient, pump intake and discharge pressures, percent oil and reservoir temperature data are used in the calculations to make the adjustments to convert the pump displacement into stock tank barrels per day. Reducing pump displacement for the impact of slippage between the plunger and the barrel depends on knowing information about the pump ran in the well and recording the plunge length and pump clearance data for use in the Patterson slippage calculations. The amount of gas in solution in the oil at intake conditions is usually small, but oil and gas gravities, percent oil from measured oil and water production rates, and the formation temperature affects the correlations that calculates gas in solution. Accurate data is important in accurate calculated results.

A representative dynamometer card should be carefully selected from the full range of pump strokes obtained during the dynamometer testing at the well, when comparing the adjusted pump displacement to the measured liquid produced into the stock tank. This new pump card analysis technique provides an enhanced trouble shooting tool for sucker for rod pumped wells. Adjustments made to pump displacement to account for gas existing inside the pump chamber, for temperature/pressure effects and for displacement losses due to pump slippage; provide to the operator a clearer picture of the amount of liquid and gas discharged from the pump into the tubing and produced into the surface stock tank. Walton E. Gilbert[3] detailed the calculations of free gas inside the pump chamber when the TV opens. The concepts of calculating free gas inside the pump chamber as discussed in this paper have been known since the 1930's.

References

1. John Patterson, Kyle Chambliss, Lynn Rowlan, Jim Curfew: "Progress Report #4 on "Fluid Slippage in Down-Hole Rod-Drawn Oil Well Pumps" ", SWPSC, Lubbock, Texas (2007)
2. Hatem Tebourski, "Two-Phase Volumetric Efficiency in Sucker Rod Pumps", The University of Tulsa Graduate School, 1995
3. W. E. Gilbert, "An Oil-Well Pump Dynagraph", Production Practice, 1936

Nomenclature:

D = nominal plunger diameter, inches

C = diametrical clearance, inches
P = Pressure drop across the plunger, psi
L = length of the plunger, inches for Patterson
SL = stroke length, inches
SPM = strokes per minute
U = pump velocity, ft/sec = SL SPM/360
μ =viscosity of fluids, cp

Figure 1 – Example of Difference in Pump Displacement Calculation and Surface Measurements

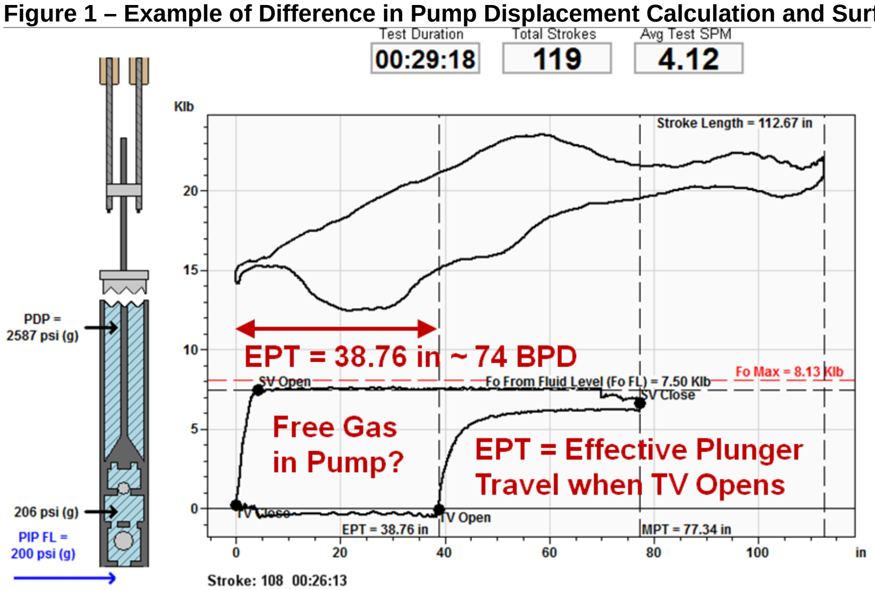

Figure 2 – Gas Compression Curve Represented on the Downstroke

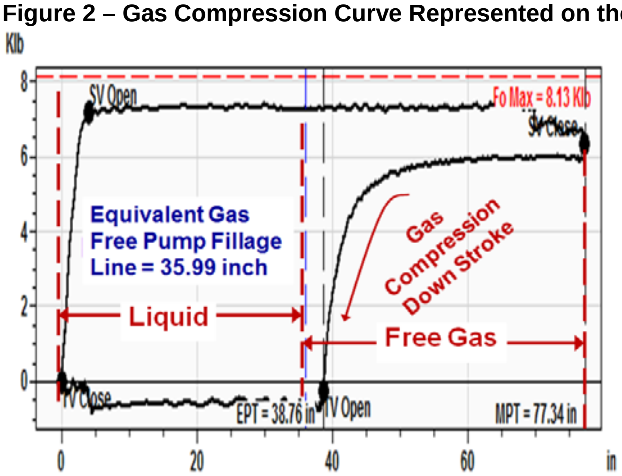

Figure 3 – Compressed Gas Volume in the Pump Chamber

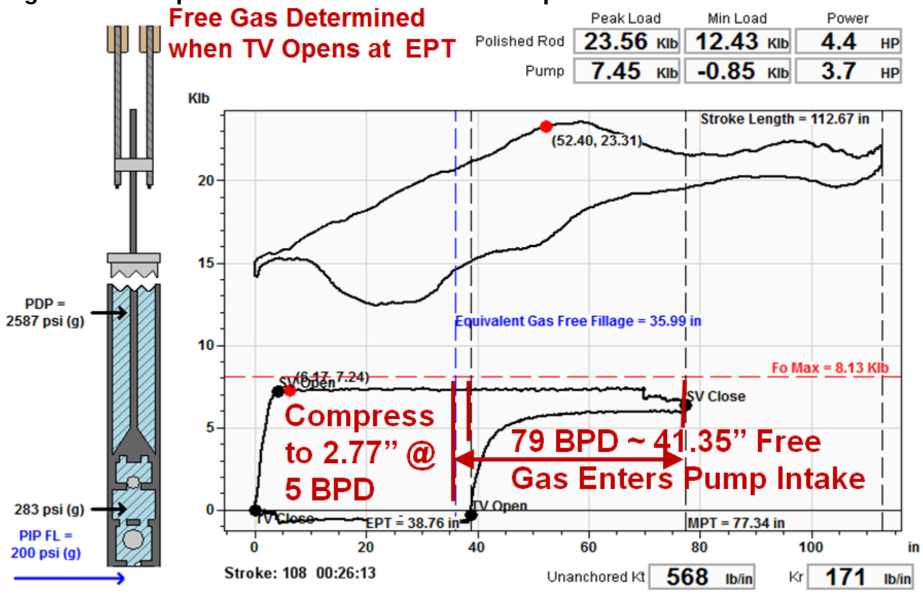

Figure 4 – Z-Factor Calculations

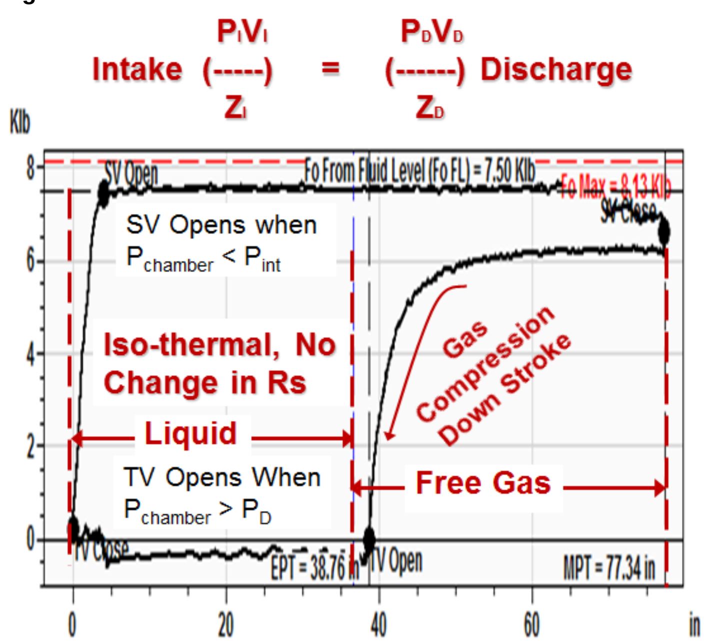

Figure 5 – Example 1: Load Lines on Up and Down Stroke Compared to Reference Loads

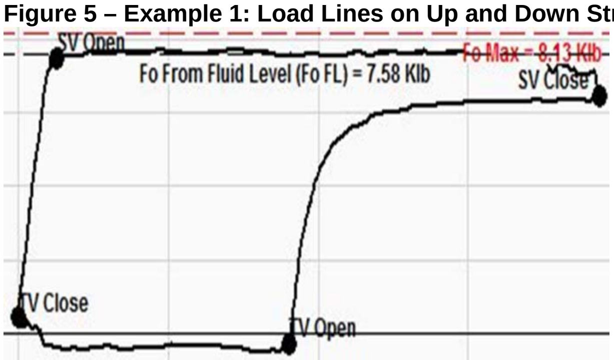

Figure 6 – Selection of Representative Stroke 104 for Analysis from Pump Card Overlay

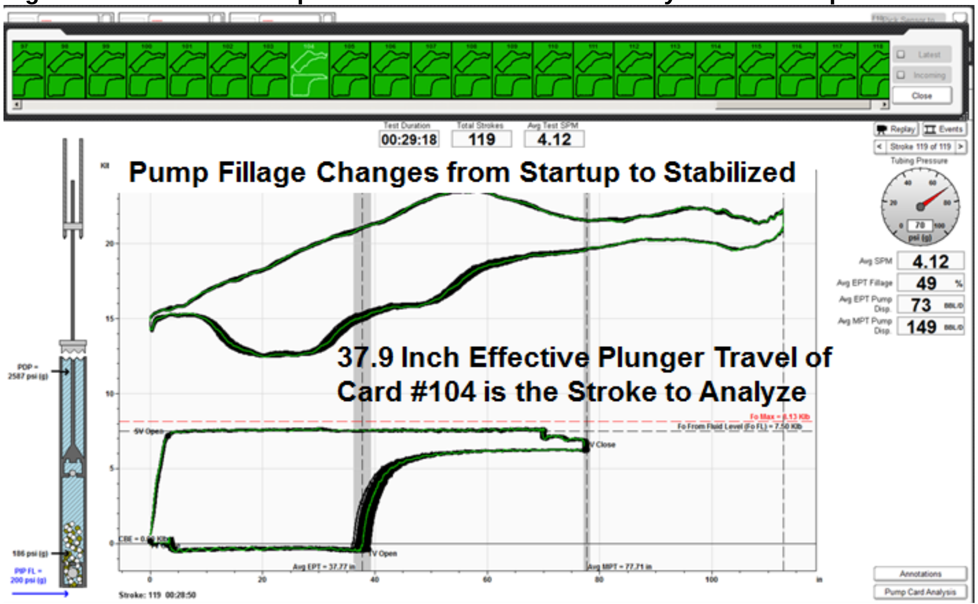

Figure 7 – Pump Card Analysis for Well A

Pump

	in	BBL/D
Maximum Plunger Travel	77.43	
Free Gas in Pump at Intake	41.73	80
Effective Plunger Stroke	37.80	73
Free Gas in Pump at Discharge	2.10	4
TV Close Delay	0.00	0
Slippage (Patterson)	5.72	11
Pump Displacement	29.99	58

Liquid

	Pump Discharge BBL/D	(Calc) Surface Stock Tank BBL/D	(Input) Surface Stock Tank BBL/D
Oil	58	53	59
Water	0	0	0
Total Liquid	58	53	59

Gas

Dissolved Gas in Oil	1772.0 scf
Total Gas Up Tubing	6.7 Mscf/D
Annular Gas from LL	9.1 Mscf/D
(Calc) Surface Gas at Standard Conditions	15.9 Mscf/D
(Input) Surface Gas at Standard Conditions	22.0 Mscf/D
System Gas Separation Efficiency	57.6 %

Figure 8 – Example 2: Well B Showing Low Gas production, High Liquid Level, and Full Pump

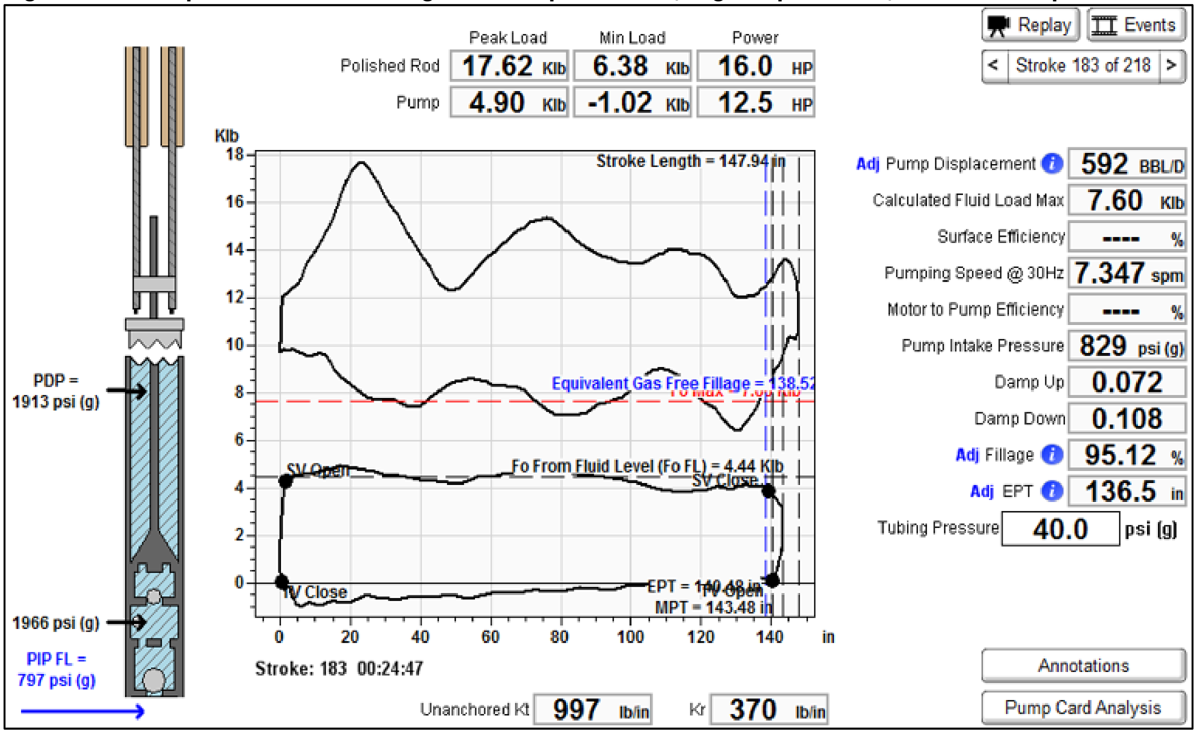

Figure 9 – Calculated Pump Discharge in Stock Tank BPD for Well B

Pump

	in	BBL/D
Maximum Plunger Travel	143.48	
Free Gas in Pump at Intake	4.97	22
Effective Plunger Stroke	140.48	609
Free Gas in Pump at Discharge	1.96	9
TV Close Delay	0.37	2
Slippage (Patterson)	1.66	7
Pump Displacement	136.49	592

Liquid

	Pump Discharge BBL/D	(Calc) Surface Stock Tank BBL/D	(Input) Surface Stock Tank BBL/D
Oil	3	3	3
Water	589	577	600
Total Liquid	592	580	603

Figure 10 – Example 3: Stroke 197 Selected as Representative Stroke for Well C

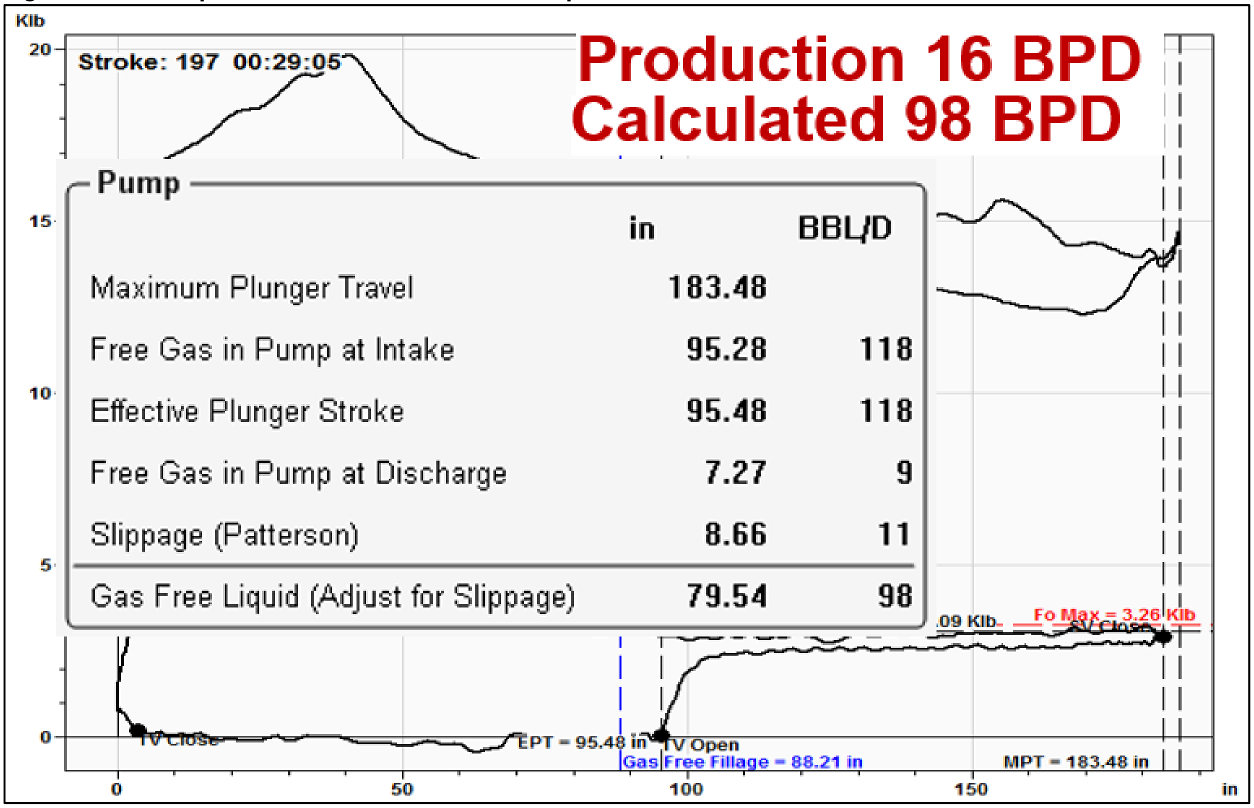

Figure 11 – Pump Card Overlay Displaying Changes in Pump Fillage on Well C

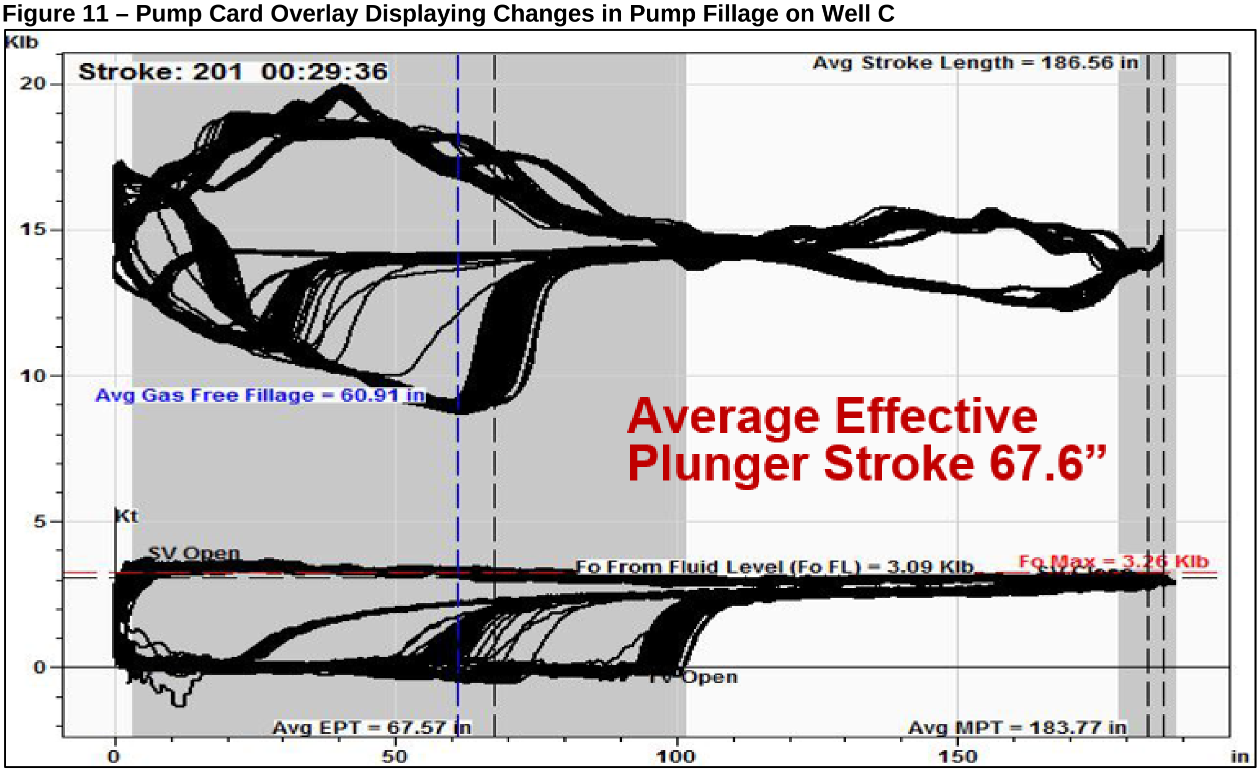

Figure 12 – Correct Stroke 2 Selected to Match Production Rate on Well C

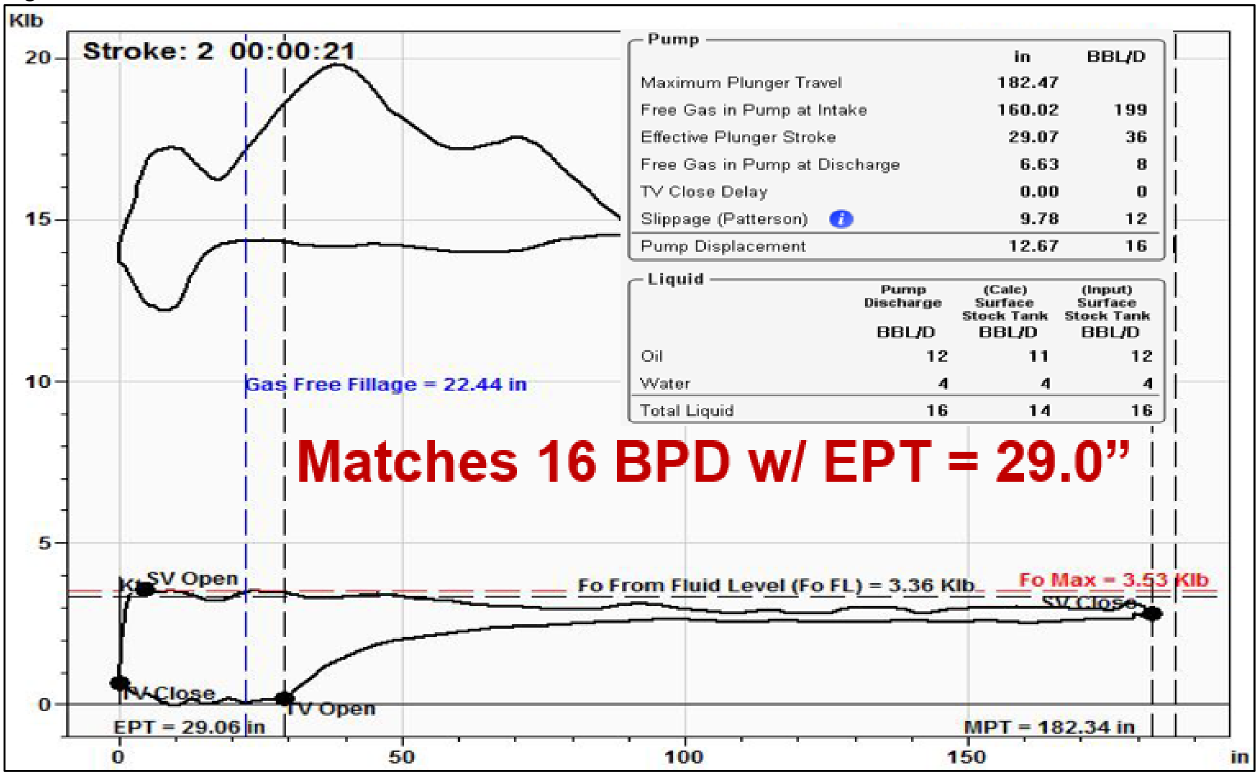

Figure 13 – Tubing Fluid Gradient Critical in Determining Gas Volume at Pump Intake Pressure on Well D

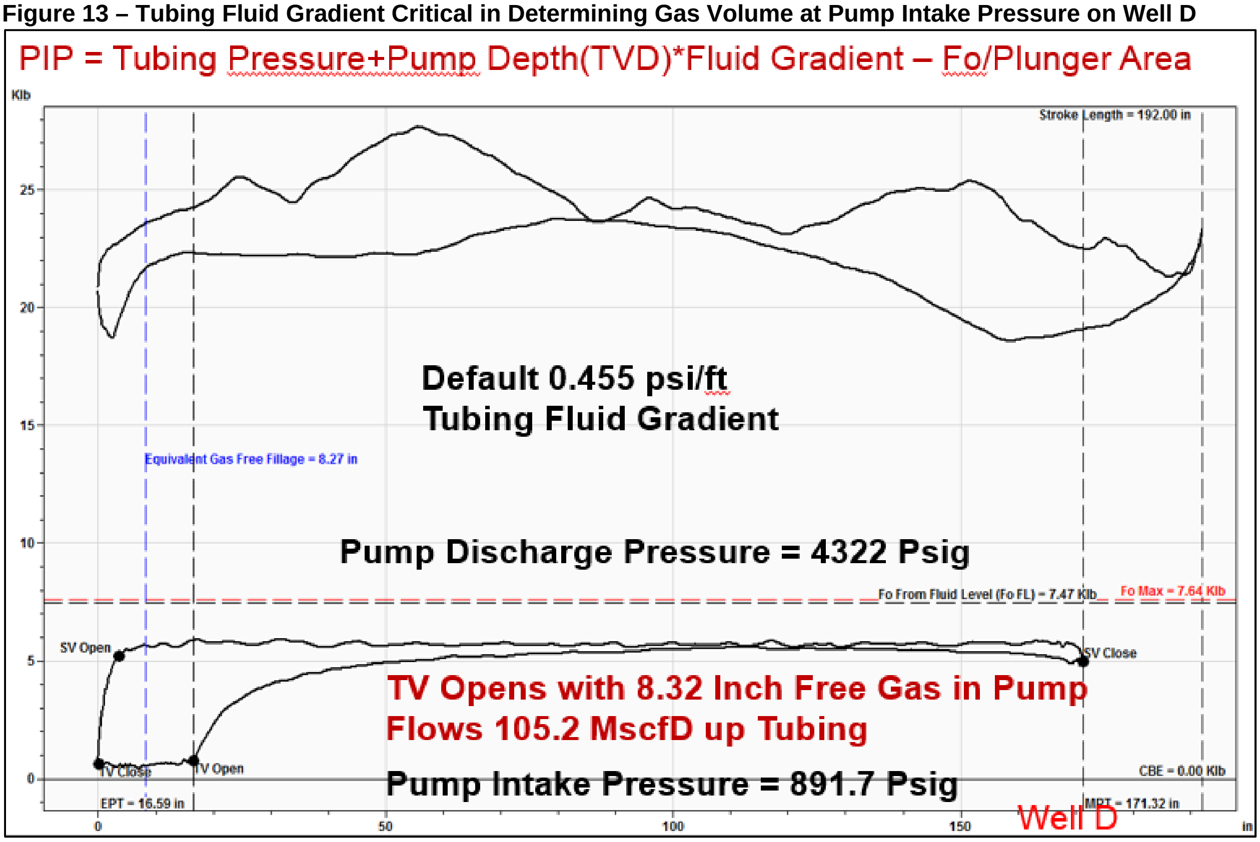

Figure 14 – Effects of Manually Adjusting Tubing Fluid Gradient on Well D

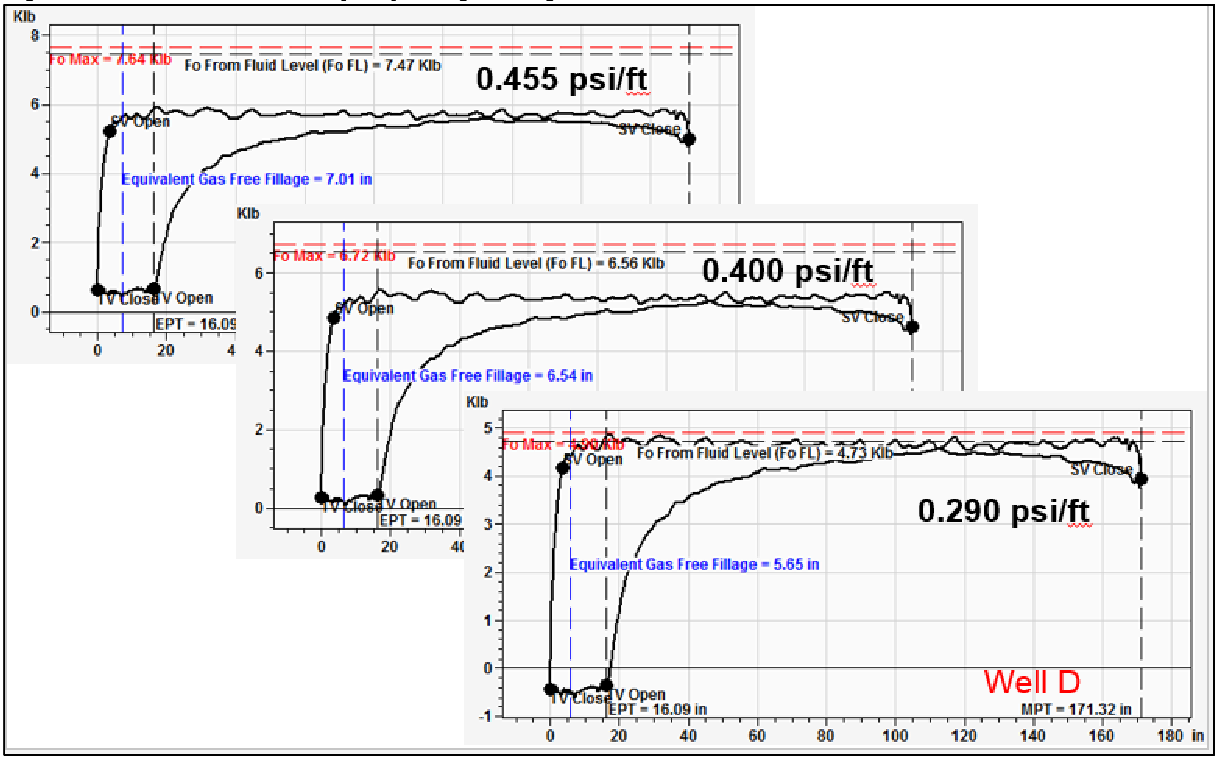

Figure 15 – Corrected Pump Analysis Using Production Data for Tubing Fluid Gradient on Well D

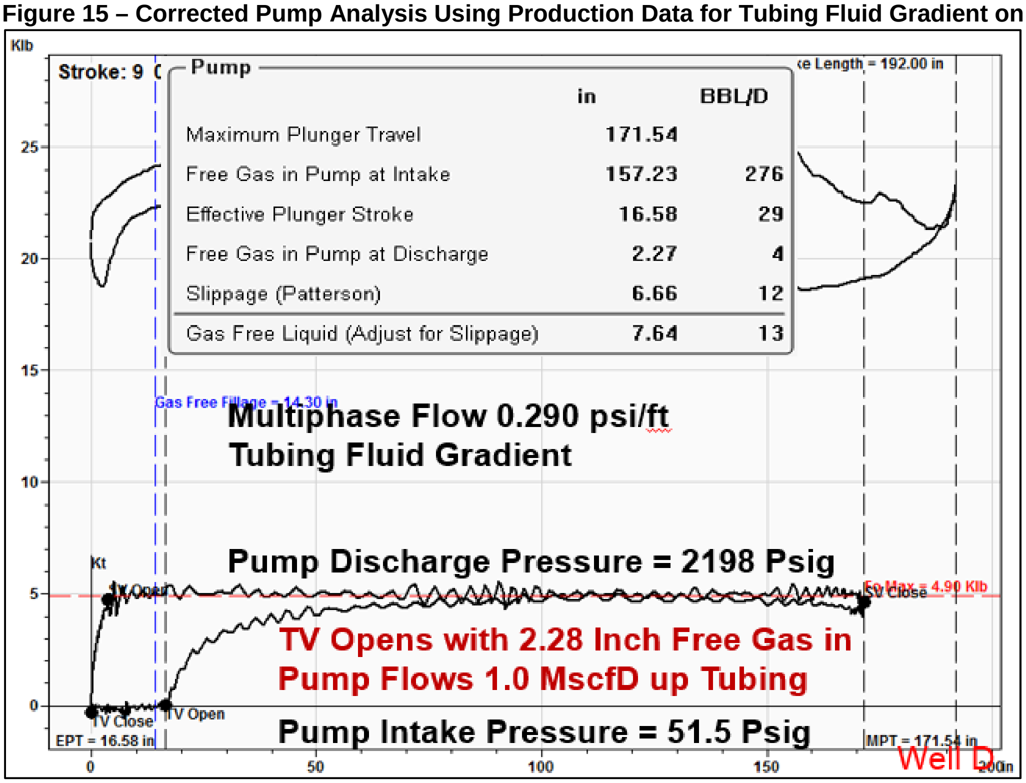

Figure 16 – High Pressure Gas at Intake Reduces Pump Fillage on Well E

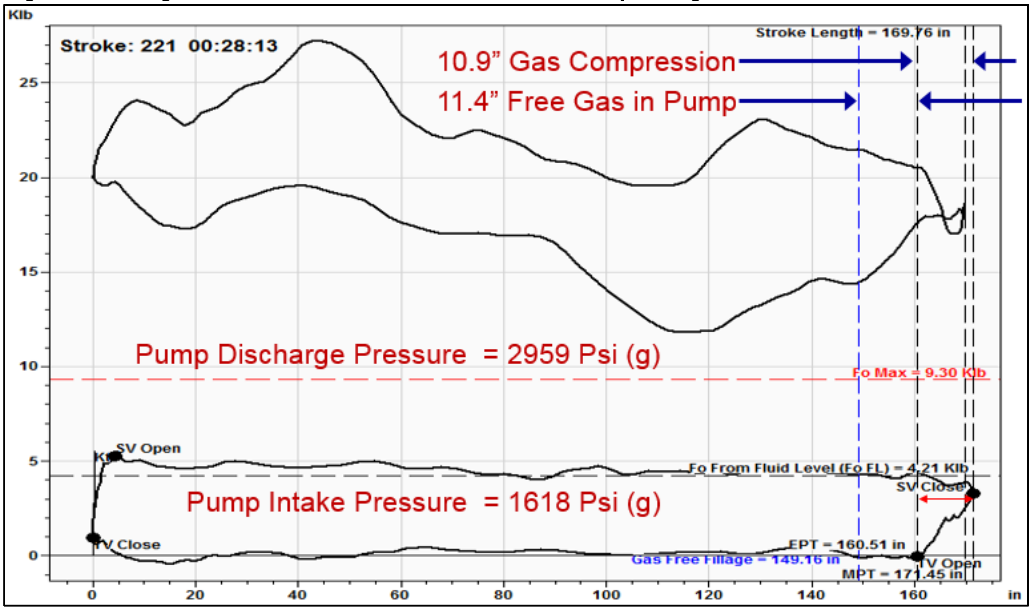

Figure 17 – Gas Interference Changes Over 30 Minute Time Interval for Well F

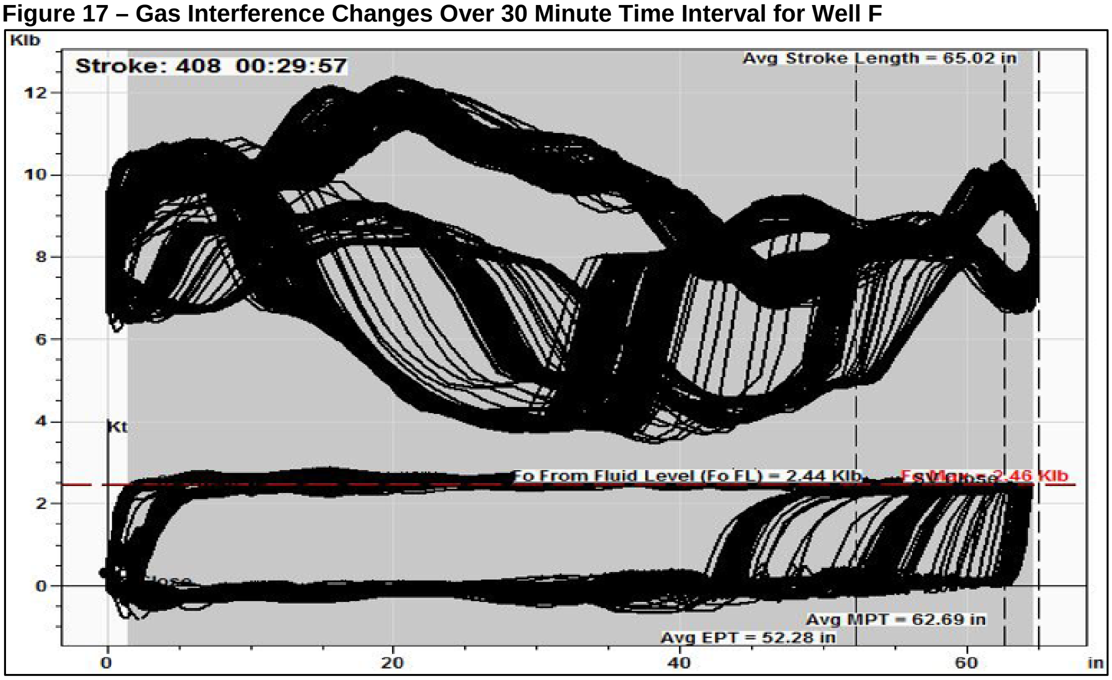

Figure 18 – Pump Stroke is Reduced when Traveling Valve Delays Going On Seat in Well F

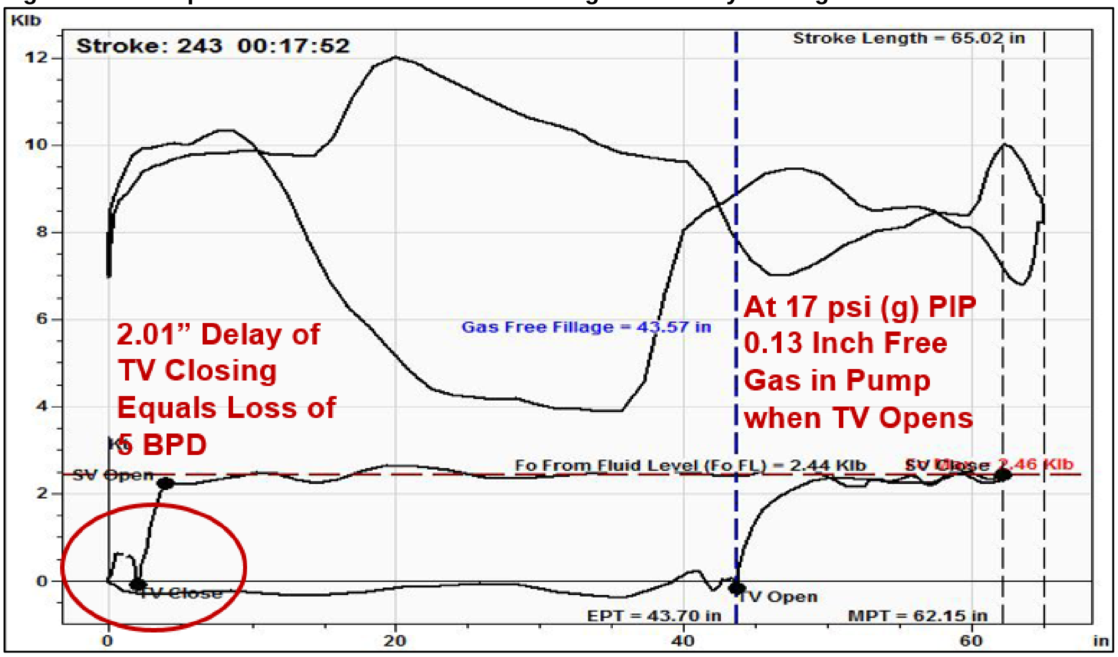

Figure 19 – Pump Card Analysis for Well F

Pump

	in	BBL/D
Maximum Plunger Travel	62.22	
Free Gas in Pump at Intake	18.77	47
Effective Plunger Stroke	43.59	108
Free Gas in Pump at Discharge	0.14	0
TV Close Delay	2.01	5
Slippage (Patterson)	5.25	13
Pump Displacement	36.19	90

Liquid

	Pump Discharge BBL/D	(Calc) Surface Stock Tank BBL/D	(Input) Surface Stock Tank BBL/D
Oil	7	7	6
Water	83	81	70
Total Liquid	90	88	76

Gas

Dissolved Gas in Oil	54.219 scf
Total Gas Up Tubing	1.2 Mscf/D
Annular Gas from LL	1.4 Mscf/D
(Calc) Surface Gas at Standard Conditions	2.6 Mscf/D
(Input) Surface Gas at Standard Conditions	1.0 Mscf/D
System Gas Separation Efficiency	54.9 %

Figure 20 – 56 BPD Calculated vs 20 BPD Measured on Well G

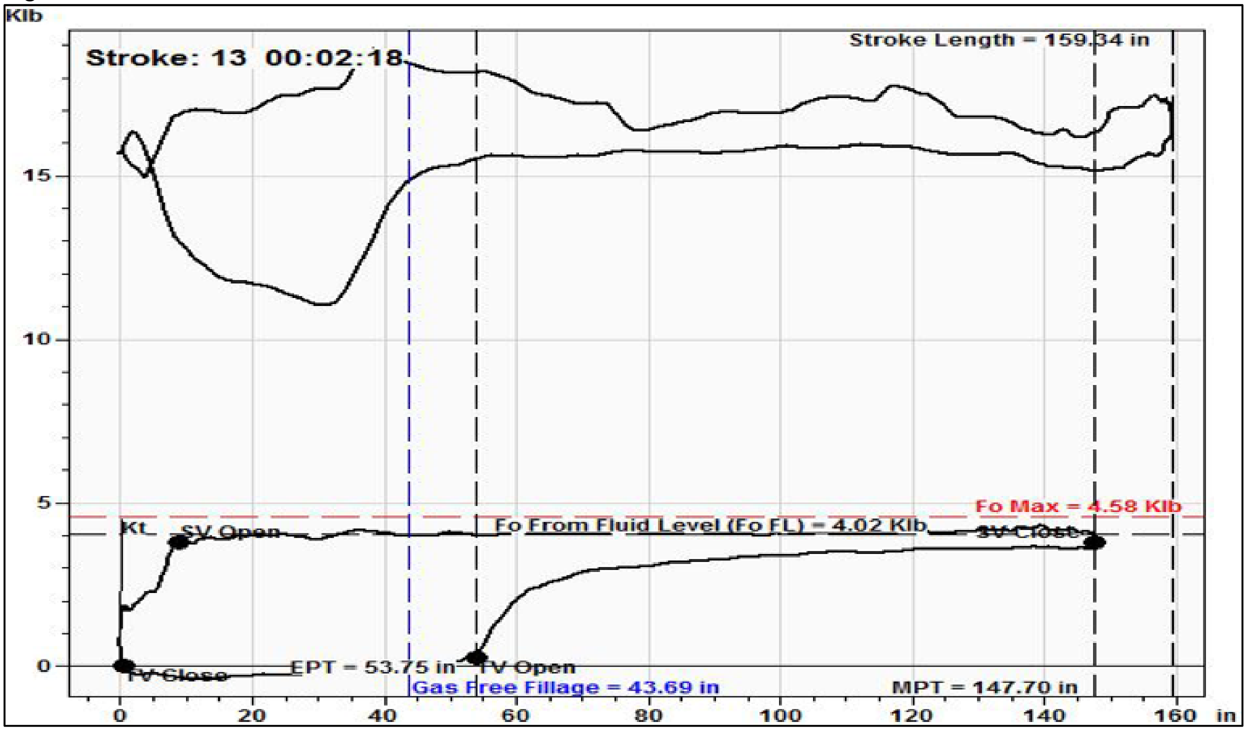

Figure 21 – Representative Stroke Concept for Well G

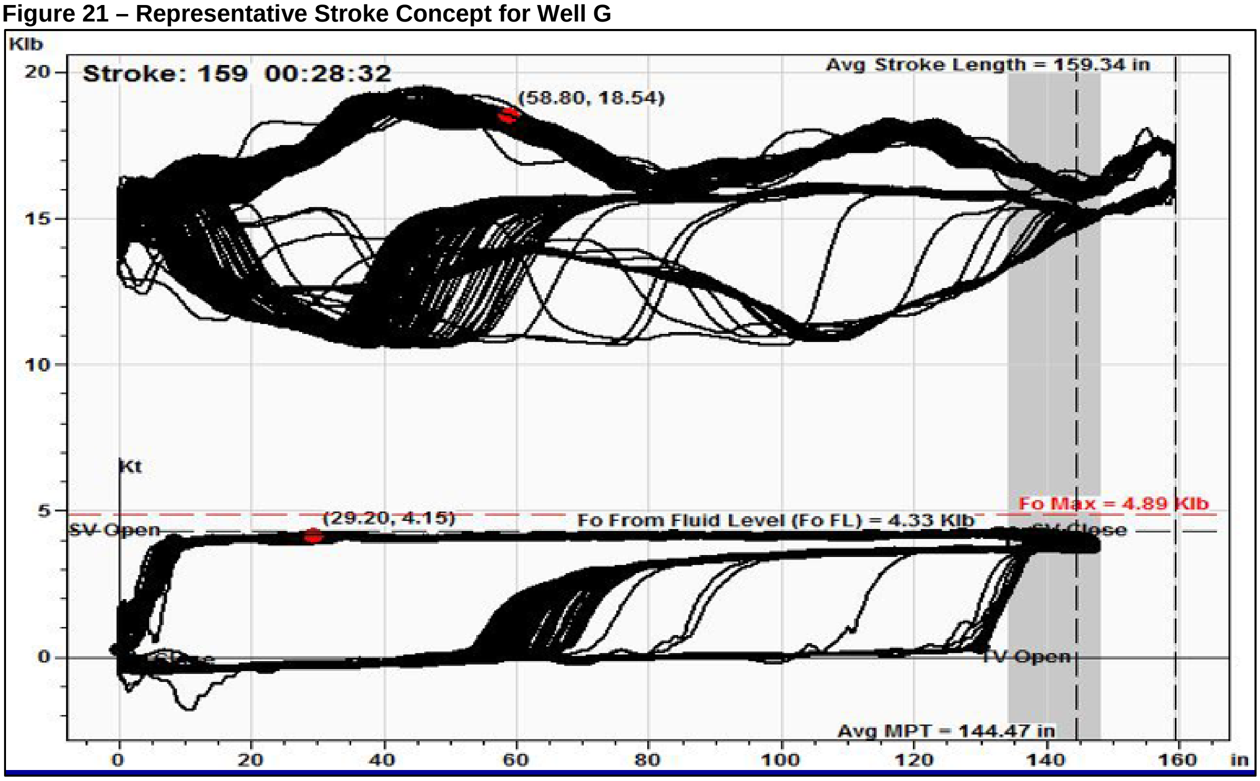

Figure 22 – Run Time Consideration for Production Rate Calculations

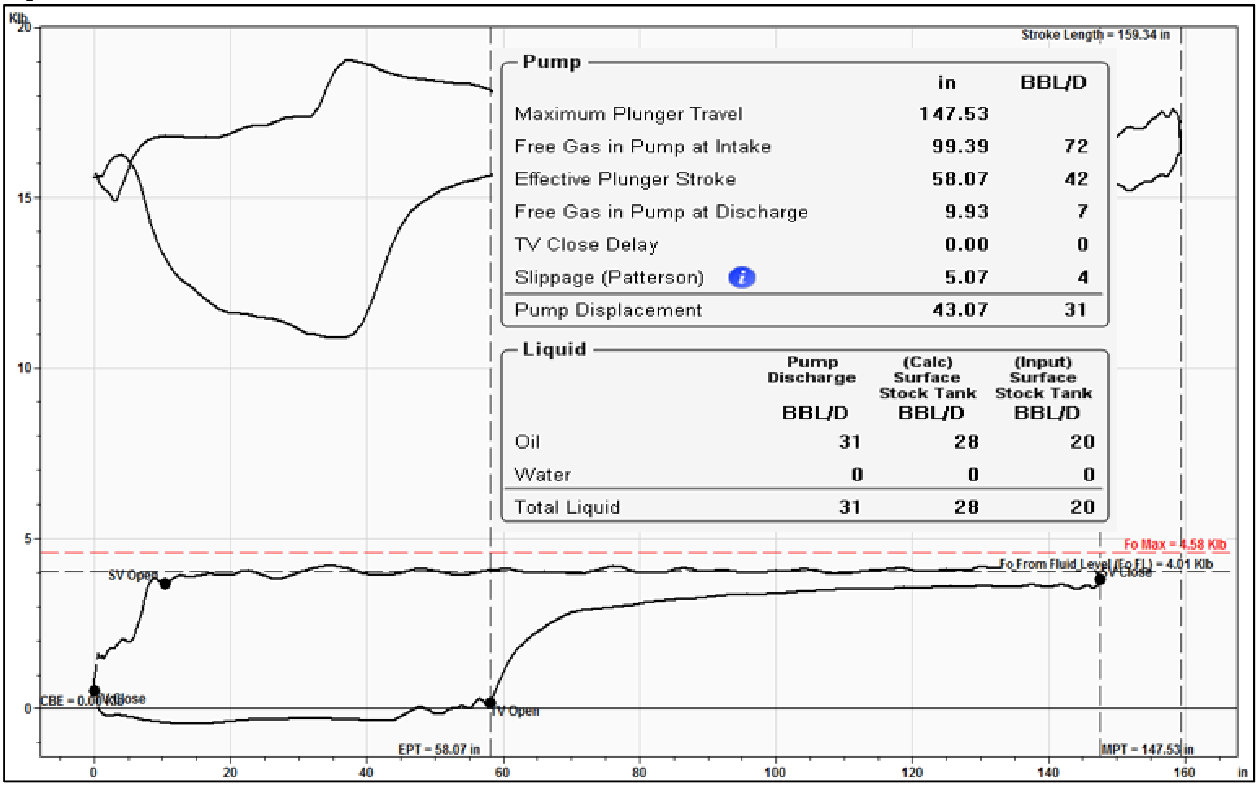

Figure 23 – Pump Card Analysis for Slippage Example

Pump

	in	BBL/D
Maximum Plunger Travel	77.34	
Free Gas in Pump at Intake	41.35	79
Effective Plunger Stroke	38.76	74
Free Gas in Pump at Discharge	2.77	5
TV Close Delay	0.00	0
Slippage (Patterson)	5.60	11
Pump Displacement	30.39	58

Liquid

	Pump Discharge BBL/D	(Calc) Surface Stock Tank BBL/D	(Input) Surface Stock Tank BBL/D
Oil	58	53	59
Water	0	0	0
Total Liquid	58	53	59