The Three Causes of Incomplete Pump Fillage and How to diagnose them correctly from Dynamometer and Fluid Level Surveys

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Abstract
Incomplete pump fillage is often associated erroneously with a “pumped-off well”, meaning that the pump displacement exceeds the production capacity of the reservoir, ignoring the fact that there are two other causes of partial liquid fillage: gas interference and the presence of a flow restriction or excessive pressure drop at the pump intake. The result of a misdiagnosis is to incorrectly set the mode of operation of pump-off controllers, variable speed drives or timers thereby loosing significant amounts of production. This paper describes the three causes of incomplete pump fillage, presents several sets of field data for the various cases, discusses how to combine dynamometer and fluid level records to correctly identify the source of the problem and presents recommendations for possible solutions.

Introduction
One of the main causes of inefficient rod pump operation is incomplete liquid fillage since this causes a reduction of the effective plunger stroke thereby reducing the volumetric displacement per pump stroke. Pump operation and performance can be analyzed in detail using a surface dynamometer measurement that is processed to compute the corresponding pump dynamometer diagram.

Figure 1 illustrates the form of the pump dynamometer diagram for a pump that is full of liquid, has valves operating correctly and without leakage and is installed in anchored tubing. The diagram is a representation of the load at the pull-rod (vertical axis) as a function of the position of the pump plunger (horizontal axis) relative to the bottom of the plunger stroke which is the axis zero. The pull rod load is the force created by the difference in pressure above and below the plunger multiplied by the cross sectional area of the plunger. This force is equal to zero when traveling valve is open and the pressure inside the pump barrel is equal to the pressure above the traveling valve (which is the pressure that exists at the bottom of the tubing string). During most to the upstroke when the traveling valve is closed and the standing valve is open, then the pull-rod load remains constant and equal to **Fo** which is defined as the “fluid load” and equal to:

$$Fo = (Pdis - Pb) * Ap \qquad (1)$$

Where:

Ap = cross sectional area of plunger, in^2
$Pdis$ = pump discharge pressure, psi
Pb = pressure inside pump barrel, psi

Assuming that the standing valve is operating normally and there are no restrictions to fluid flow from the wellbore into the pump the pressure inside the pump barrel during the upstroke is slightly less than the pump intake pressure by the frictional pressure losses due to the flow. These losses are generally of the order of 5 to 10 psi for water and low viscosity oils. The pump intake pressure (defined as **PIP**) is determined by the pressure that exists in the annulus at the depth of the pump seating nipple and is directly related to the gas-free liquid pump submergence and the casing head pressure.

The pump discharge pressure, defined as **Pdis**, is the pressure that exists at the bottom of the tubing and is equal to the sum of the tubing head pressure plus the pressure due to the column of fluid in the tubing down to the top of the traveling valve. The tubing fluid is a mixture of oil, water and gas and its gradient is normally computed from the density of the produced oil and water mixed in proportion to the well test water-oil ratio.

The maximum value of Fo is labeled **FoMax**. It is an important reference quantity that is used in diagnosing pump operation from analysis of the pump dynamometer card. It is computed as follows:

$$FoMax = (Pdis) * Ap \qquad (2)$$

The assumption is that the pressure in the pump barrel is equal to zero. In practice, this assumption implies that the pump intake pressure is zero. The pump intake pressure (defined as **PIP**) is determined by the pressure that exists in the annulus at the depth of the pump seating nipple and is directly related to the gas-free liquid pump submergence and the casing head pressure. Therefore a zero pump intake pressure can be achieved only if there is no annular liquid above the pump intake and the casing head pressure is atmospheric.

Since FoMax represents the maximum fluid load that can be applied to the pull rod by the pump, then a situation where the value of **Fo** in a pump dynamometer card exceeds the value of **FoMax** is indication of some abnormal condition in the system or an error in the data describing the pump, fluid properties or other well parameters.

The total distance traveled by the plunger during the upstroke is defined as the Maximum Plunger Travel or **MPT** where a value of zero corresponds to the bottom of the stroke. The distance traveled by the plunger during which fluid is discharged from the barrel through the traveling valve is defined as the Effective Plunger Travel or **EPT**. This distance multiplied by the cross sectional area of the plunger is equal to the volume of fluid displaced by the plunger for one stroke. The daily displacement of the pump is obtained by multiplying this volume times the number of strokes per 24 hours. When the barrel is completely filled with liquid (as in **Figure 1**) the **EPT** and the **MPT** are equal.

Incomplete Liquid Fillage

Figure 2 illustrates a pump dynamometer diagram for a pump where the barrel is not completely filled with liquid when the plunger reaches the top of the stroke. The sequence of pump operation is as follows:

- At point A both traveling valve (TV) and standing valve (SV) are closed
- The plunger moves up a very short distance (~0.1 inch) causing the pressure in the barrel to drop below the value of the pressure at the pump intake.
- The SV opens at point B
- Fluid present at the pump intake (gas and liquid) flows through the SV and fills the barrel as the plunger moves from B to the top of the stroke at C.
- Both TV and SV close at point C. The fluid in the pump barrel is a mixture of gas and liquid that exhibits a high compressibility.
- The plunger moves down several inches (6 inches) from C to D, compressing the fluid mixture and increasing the pressure in the barrel below the TV.
- The barrel pressure exceeds the pump discharge pressure Pdis at point D where the TV opens.
- Fluid in the barrel is transferred to the tubing as the plunger slides to the bottom of the stroke from D to A.

Comparing the diagram in **Figure 2** (partial fillage) to that in **Figure 1** (100% fillage) the main difference is observed during the beginning of the down stroke from point C to point D. The difference is caused by presence of the gas in the pump barrel. The gas requires a greater plunger travel from the top of the stroke to compress the fluid mixture to the PDP. The greater the volume of low pressure gas inside the pump at the top of the plunger stroke, the greater the distance that the plunger has to move to compress the fluid inside the pump barrel to the discharge pressure required to open the TV.

The shape of the load-position curve from C to D depends on the volume of gas entering the pump barrel during the up stroke and the pressure of the gas when the plunger reaches the top of the stroke. In general the pressure in the barrel during the upstroke is close to the pump intake pressure PIP.

Figure 3 illustrates an example of how the pump intake pressure affects the plunger travel and the shape of the pump dynamometer diagram during the down stroke when the barrel is only 50% filled with liquid.

The pressure-volume relation during compression of the fluid in the barrel assumes real gas behavior at isothermal conditions and that any free gas is not dissolved in the liquid. The graph is a plot of the pump rod load (Lbs) as a function of the plunger distance from the bottom of the stroke from 0 to 90 inches. The barrel is 50% filled with liquid so that the gas liquid interface is located at 45 inches from the bottom of the stroke. The pull rod load is computed as the difference between the pump discharge pressure (2000 psi) and the barrel pressure multiplied by the cross sectional area of the 1.5 inch diameter plunger. Five graphs are displayed that correspond to different pressures of the gas in the barrel at the top of the stroke depending on values of the PIP from 10 to 500 psi. The pressure in the pump barrel as a function of plunger position is computed from the following relation:

$$P2 = \frac{P1 * V1 * Z2}{V2 * Z1} \qquad (3)$$

Where:

P1= PIP

P2=Pdis

V1=initial gas volume in barrel when plunger is at 90 inch.
V2=gas volume in barrel at new plunger position.
Z1=gas super compressibility factor at PIP
Z2= has super compressibility factor at P2

The solution is iterative since Z_2 is a function of P_2. The temperature is assumed to remain constant.

When the initial barrel pressure is low (10 psi, top curve) the pump load at C is high and remains almost constant while the plunger moves down from 90 to 65 inches then the load begins to decrease slowly to 50 inches and finally decreases rapidly from 50 to 46 inches where the TV opens. The behavior of the pump load corresponds to a very low pressure in the barrel so that the fluid load initially is close to FoMax and the pressure does not increase appreciably as the plunger moves on the down stroke until it gets close to the gas liquid interface that is at 45 inches from the bottom. This form of the downstroke load vs. position curve is labeled "fluid pound".

When the initial barrel pressure is high (500 psi, bottom curve) the pump load at C is lower than FoMax and starts decreasing as soon as the plunger begins the down stroke. At point D the plunger is at 60 inches from the bottom, the pressure in the gas has increased to the discharge pressure of 2000 psi, the TV opens and gas flows through the TV into the tubing. The fluid distribution in the pump for this case is illustrated in **Figure 4**. This form of the downstroke load vs. position curve is labeled "gas interference".

For intermediate values of the PIP the form of the load-position curve changes gradually from fluid pound to gas interference. These features of the pump dynamometer card are some of the tools used in determining the cause of incomplete pump fillage as shown in the subsequent sections.

Causes of Incomplete Liquid Fillage of the Pump

The causes of incomplete liquid fillage can be classified in three categories:

1- Fluid present at the pump intake consists of a mixture of free gas and liquid and consequently both phases enter the pump through the standing valve. This condition is normally labeled "<u>gas interference</u>".
2- Production liquid rate from the reservoir (flowing through perforations) is less than the pump displacement rate and consequently there is not sufficient liquid in the annulus to fill the pump barrel. This condition is normally labeled "<u>pumped off</u>"
3- Flow rate of liquid entering the pump is restricted so that the liquid cannot fill the pump barrel fast enough during the plunger upstroke. Flow restriction may be caused by deposits of scale, paraffin, sand, rust or other materials or by excessive friction losses related to viscous crude. This condition is normally labeled "<u>choked pump</u>"

For the three cases the pump dynamometer diagram will show that incomplete liquid fillage is present but only a more detailed analysis will determine with certainty which is the source of the problem as shown in the following sections.

<u>**Cause 1 – Gas interference**</u>

This situation, illustrated in **Figure 5**, is most common when the pump intake is set above the producing formation and free gas is flowing from the perforations giving rise to a gas-liquid mixture being present in the wellbore from the perforations up to the pump intake. A portion of the gas will enter the pump with the liquid while the rest is normally produced as it flows to the surface through the casing tubing annulus. The presence of free gas flow can be verified by observing that the casing head pressure increases when performing an acoustic fluid level survey and the casing to flow-line valve is closed momentarily. The rate of pressure increase (psi/minute) is directly proportional to the gas flow rate that can be computed knowing the annular volume and gas gravity.

Figure 6 shows analyses of dynamometer and fluid level data for a typical case of gas interference. The pump intake is at 5059 feet while the perforations are at 5390 feet. Gas is flowing up the annulus at a rate of about 126 MSCF/day aerating the liquid into a gaseous liquid column with an average liquid content of 28% and a height of 4900 feet. The casing head pressure of 243 psi combined with the pressure due to the gaseous liquid column result in a pump intake pressure of 730.7 psi. The pump dynamometer card exhibits incomplete liquid fillage. The upstroke portion of the pump dynamometer aligns with the value of the fluid load (Fo about 4500 Lbs) computed from the pump intake pressure obtained from the fluid level survey. The pump card load on the upstroke is much less than the value of FoMax which is computed as 7300 Lbs.

The down stroke portion of the pump dynamometer shows the load decreasing as soon as the plunger begins downwards motion and follows the typical hyperbolic shape due to gas compression. The maximum plunger travel (MPT) is 155 inches while the effective plunger travel (EPT) is 64.3 inches corresponding to the position of the vertical dashed line at the point where the TV opens. For this pump operating at 8.45 strokes per minute with a 2-1/4 inch plunger the effective pump displacement is 320 Bbl/day.

Figure 7 shows a detailed analysis of the polished rod velocity, the plunger velocity and pump load as a function of time for the complete stroke. The vertical dashed line indicates the point where the TV opens after the gas in the barrel is compressed to the pump discharge pressure. Notice how the velocity of the plunger at the beginning of the down stroke from 4 seconds to 5 seconds follows exactly the velocity of the polished rod reaching a maximum velocity of about 91 inches per second. From this point to about 5.5 seconds both the polished rod and the plunger slow down, but the plunger slows down more due to the resistance from compressing gas. At the point where the TV opens the plunger is moving at 54 inches per second while the polished rod is moving at 86 inches per second. This velocity difference causes compressive loading of the rods as indicated by the negative pump load of 370 Lbs. After the TV opens (from 5.5 to 6.1 seconds) the plunger velocity increases to 77 inches per second, exceeding the downward velocity of the polished rod. These velocity variations cause the load oscillations noted at the bottom of the pump dynamometer card. Compressive loading of the lower section of the rods results in helical buckling of the rods and excessive wear of the tubing.

Cause 2 – Well Pumped-Off

This situation, illustrated in **Figure 8**, is caused by a mismatch between the pump displacement rate and the production rate of liquid from the reservoir. As illustrated in the figure when the daily pump displacement rate is 100 bbl/day and the inflow from the formation is only 30 bbl/day, once the well has stabilized then the liquid fillage of the pump barrel will be about 30%.

The fluid level in the annulus will be at the depth of the tubing intake which may be deeper than the depth of the standing valve in those wells where a tail pipe or a gas anchor has been installed.

The pressure at the pump intake is generally very low and slightly greater than the casing head pressure. Consequently the pressure in the pump barrel when the plunger reaches the top of its stroke will also be very low. The pump load during the upstroke will be a high value very close to the value of FoMax. A typical example of dynamometer and fluid level analysis in a pumped off well is presented in **Figure 9**.

The pump intake is at 5173 feet while the perforations are at 5247 feet. Gas is flowing up the annulus at a rate of about 58 MSCF/day aerating the liquid into a gaseous liquid column with an average liquid content of 29% and a height of 11 feet. The casing head pressure of 35.2 psi combined with the pressure due to the gaseous liquid column result in a pump intake pressure of 40.5 psi. The pump dynamometer card exhibits incomplete liquid fillage. The upstroke portion of the pump dynamometer aligns with the value of the FoMax computed at 3863 Lbs

The down stroke portion of the pump dynamometer shows the load remaining practically constant from the point where the plunger begins downwards motion until it has traveled 15 inches and then follows the typical sharp hyperbolic decline characteristic of compression of low pressure gas. The maximum plunger travel (MPT) is 85.3 inches while the effective plunger travel (EPT) is 52.7 inches corresponding to the position of the vertical dashed line at the point where the TV opens. For this pump operating at 9.8 strokes per minute with a 1-1/2 inch plunger the effective pump displacement is 135.2 Bbl/day.

Figure 10 shows a detailed analysis of the polished rod velocity, the plunger velocity and pump load as a function of time for a complete stroke. Notice how the velocity of the plunger at the beginning of the down stroke from 5 seconds to 7.2 seconds follows roughly the velocity of the polished rod reaching velocity of about 35 inches per second. From this point to about 7.6 seconds both the polished rod and the plunger slow down, but the plunger almost stops at the point where it reaches the gas-liquid interface in the barrel and the TV opens. At this point (8 seconds) the plunger is moving at 3 inches per second while the polished rod is moving at 30 inches per second. This rapid velocity differential causes a minor amount of compressive loading of the rods as indicated by the negative pump load of 180 Lbs. After the TV opens (from 8 to 9 seconds) the plunger velocity increases to 33 inches per second, exceeding the velocity of the polished rod. This variation causes the load oscillations noted at the bottom of the pump dynamometer.

Compressive loading of the lower section of the rods results in helical buckling of the rods and excessive wear of the tubing. Impact loading is also transmitted throughout the rod string and is felt at the polished rod from where is derived the name “fluid pound”, even though the negative load on the downstroke is small.

Cause 3 – Choked Pump

This condition is illustrated in **Figure 11** that represents a rod pumped well exhibiting partial liquid fillage although adequate liquid is present above the pump intake and annular gas flow is insignificant. Resistance to liquid flow through the pump intake causes the pump barrel to be incompletely filled by the time the plunger reaches the top of its stroke. The resistance to flow may be caused by scale, paraffin, corrosion, sand or other solid material plugging the passage ways through the pump intake and standing valve. In addition whenever the produced crude is viscous the frictional losses for the flow rate required to fill the barrel during the upstroke time (only 3 seconds when pumping at 10 strokes per minute) may exceed the available pump intake pressure and thus the inflow of liquid into the pump occurs at a much lower rate than that required to keep up with the plunger displacement. In this case proper sizing of the SV and intake piping is critical to obtaining better pump fillage.

The large pressure drop at the intake results in a very low pressure inside the pump barrel. The pressure below the traveling valve could be as low as the vapor pressure of the liquid at the downhole temperature in those cases of total blockage of the intake. In most cases the pressure is likely to be near atmospheric so that the pump load during the upstroke will be a high value very close to the value of FoMax.

The general form of the pump dynamometer for a choked pump is very similar to that exhibited in the "pumped-off" case. For this reason the choked pump condition is often not recognized and the well is misdiagnosed as a pumped-off well. The correct diagnosis can be reached only if a fluid level measurement is made simultaneously with the dynamometer survey as shown in **Figure 12**.

In this well a crow strainer was installed at the intake of the pump at bottom of the SV assembly. This filter is cone shaped with holes 1/8 to 1/16 inch diameter. As the pump was run, rust inside the tubing was wiped off and when seated, the holes and all around the crow filter became packed with rust completely plugging the intake.

The fluid level survey shows the liquid level at a depth 4024 feet with almost no gas (57 SCF/D) flowing up the annulus, resulting in a pump submergence of 4306 feet of liquid which combined with a casing head pressure of 50.3 psi results in a pump intake pressure of 1492 psi.

The pump dynamometer diagram shows that the upstroke load is very close to the computed value of FoMax and well above the value of Fo computed from the pump intake pressure calculated from the fluid level survey. The maximum plunger stroke is 106.7 inches and the effective plunger stroke is 23.1 inches which corresponds to 21.68 percent pump fillage. Note the severe vibrations and negative load that are developed at the point where the traveling valve opens (marked by vertical dashed line indicating that the plunger impacts the gas-liquid interface present in the pump barrel. One important question is: if the intake is completely plugged, where does liquid come from? The only possible answer is: from the tubing above the pump via plunger-barrel slippage and/or traveling valve leakage. In this case, no fluid was being produced at the surface so the pump displacement of 26.9 Bbl/day corresponds to the volume leaking and slipping from the tubing into the pump.

The negative load that occurs at the point of impact with the liquid in the barrel can be investigated in more detail by exporting the dynamometer data to a spreadsheet as shown in **Figure 13** where all the data points (sampled at a rate of 30 per second) are shown for the specific pump stroke in **Figure 12**. Note the large negative load of 1780 Lbs that occurs after the point of impact where the TV opens fully. Expanding the graph in the area between 22 and 27 inches, shown in **Figure 13**, we note that the plunger load oscillates between positive and negative values ranging from +500 to -700 Lbs indicating vibrations during which the TV chatters (opens and closes rapidly between points 2 and 3) as the plunger vibrates up and down about 1 inch. Finally the TV opens fully at point 4 and the plunger travels to the bottom of the stroke. This effect has been likened to a “head-on train wreck” and causes severe buckling with damage to the pump, tubing and rods.

Detailed analysis of plunger load and velocity are presented in **Figure 15**. During the down stroke note the rapid stopping of the plunger from a downwards velocity of 50 inches per second to zero and a few inches per second upwards at the point of impact with the liquid, while the polished rod follows a near normal velocity. The cause of the large negative impact load is the change in momentum of the rod string as the plunger stops while the polished rod continues moving at normal speed.

Summary and Recommendations

Figure 16 summarizes the characteristics of the three main causes of incomplete pump fillage as observed from the quantitative analysis of the pump dynamometer diagram and the fluid level survey as follows:

<u>Gas Interference:</u>

- Upstroke pump load Fo is less than FoMax and matches the value of Fo computed from fluid level survey.
- During down stroke the pump load starts decreasing as soon as the plunger starts downwards motion.

<u>Fluid Pound:</u>

- Upstroke pump load Fo is equal to FoMax
- Down stroke pump load remains constant during first part of plunger downwards motion, due to large change in plunger position is required to increase pressure inside pump barrel.
- Fluid level is at the pump intake, Fo computed from fluid level survey is close to FoMax
- Pump intake pressure level is close to casing head pressure.

<u>Choked Pump:</u>

- Upstroke pump load Fo is equal to FoMax
- Down stroke pump load remains constant during first part of plunger downwards motion
- Fluid level is above pump intake
- Fo computed from fluid level survey is much lower than FoMax
- Pump intake pressure from fluid level is much higher than casing head pressure
- Negative load peaks observed where TV opens

Accurate analysis of the dynamometer and fluid level records require that care be taken when acquiring the information. Following are some recommendations to follow in order to insure the accuracy of the measurements.

<u>Quality Control of Dynamometer Measurements</u>

- Requires stabilized conditions: verify that the pump is operating as it normally operates when undisturbed. Minimize downtime for installation of load cell.
- True vertical pump depth: include wellbore deviation data to correctly compute loads and pressures

- Oil, water and gas densities: required to compute gradients of annular and tubing fluids.
- Oil, water, and gas production rate: required to verify that pump displacement is representative of normal pump operation.
- Tubing head pressure: required for correct calculation of FoMax
- Tubing fluid gradient: required for correct calculation of FoMax
- Plunger diameter: required for correct calculation of FoMax
- Rod string description: required for correct calculation of pump dynamometer card
- Damping coefficients: required for correct calculation of pump dynamometer card
- Accurately installed and calibrated load sensors should be used whenever possible.

Quality Control of Fluid Level Measurements

- Requires stabilized conditions: verify that fluid level is steady
- Determination of Liquid Level Depth: obtain a clear indication fluid level echo and accurate measurement of round trip travel time.
- Correct average tubing joint length: required to calculate distance to fluid level.
- Wellbore deviation: required to compute pressure in wellbore and at pump intake
- Measurement of casing pressure: required for correct calculation of pump intake pressure
- Measurement of casing pressure change vs. time: required to calculate annular gas flow rate.
- Tubing, Casing diameters: required for calculation of annular gas rate and liquid fraction in the annulus.
- Oil, water and annular gas densities: required for calculation of pressure gradients
- Measurements should be repeated whenever excessive acoustic noise is present and fluid level echo is not clearly identifiable.

Conclusion

The three causes of incomplete pump fillage can be correctly diagnosed by using representative dynamometer and fluid level surveys. The location of the pump loads location w/ respect to the zero load line, Fo from the Fluid Level, and the Fo Max Load can be used to identify the cause of incomplete pump fillage. The pump cards for Fluid pound and Choked Intake condition look similar except that: 1) for Fluid Pound the Fluid level is at Pump Intake and 2) for Blocked Intake the Fluid Level High is high above the Pump Intake. Fluid Pound and Gas Interference both have low pressure gas in the pump that must be compressed from [C-D]. When fluid entry into the pump is blocked by a choked intake, then no gas is in the pump barrel and Plunger actually “collides” into the liquid inside the pump barrel. Large negative compressive loads are only seen when the plunger collides with the liquid inside the pump barrel of a choked intake. Large negative loads are not usually seen when the plunger contacts the liquid in cases of gas interference or fluid pound, because gas compression reduces the plunger velocity before the plunger contacts the liquid in the bottom of the pump barrel.

Figures

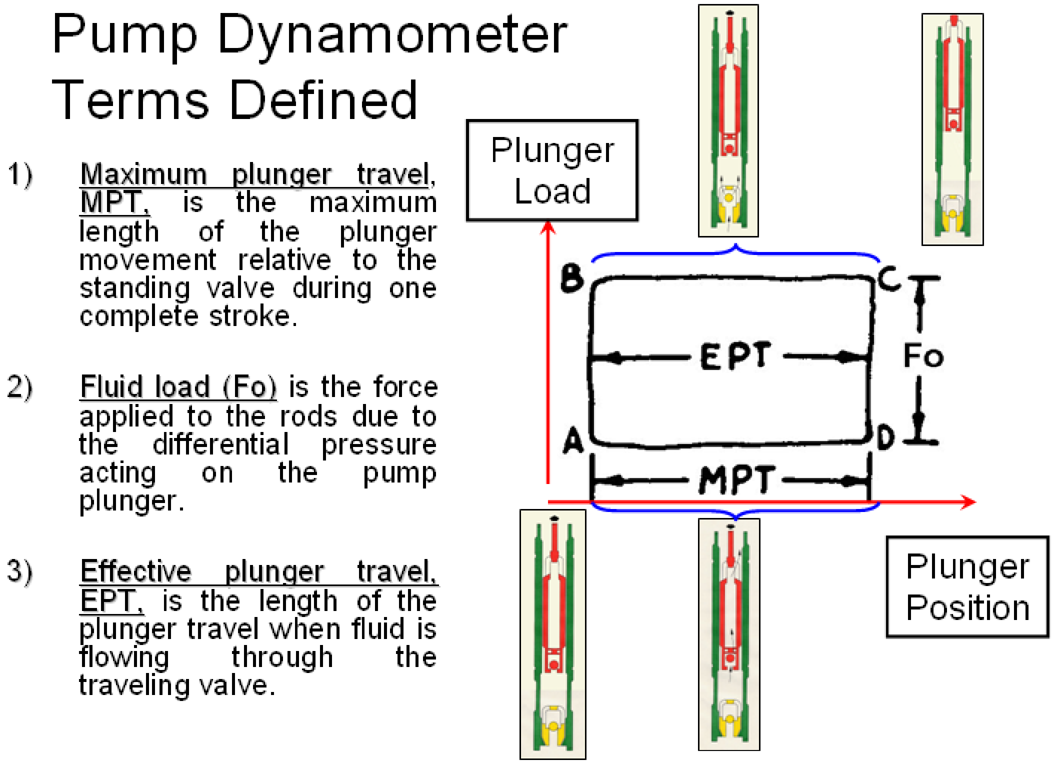

Figure 1 – Definition of pump dynamometer card reference points.

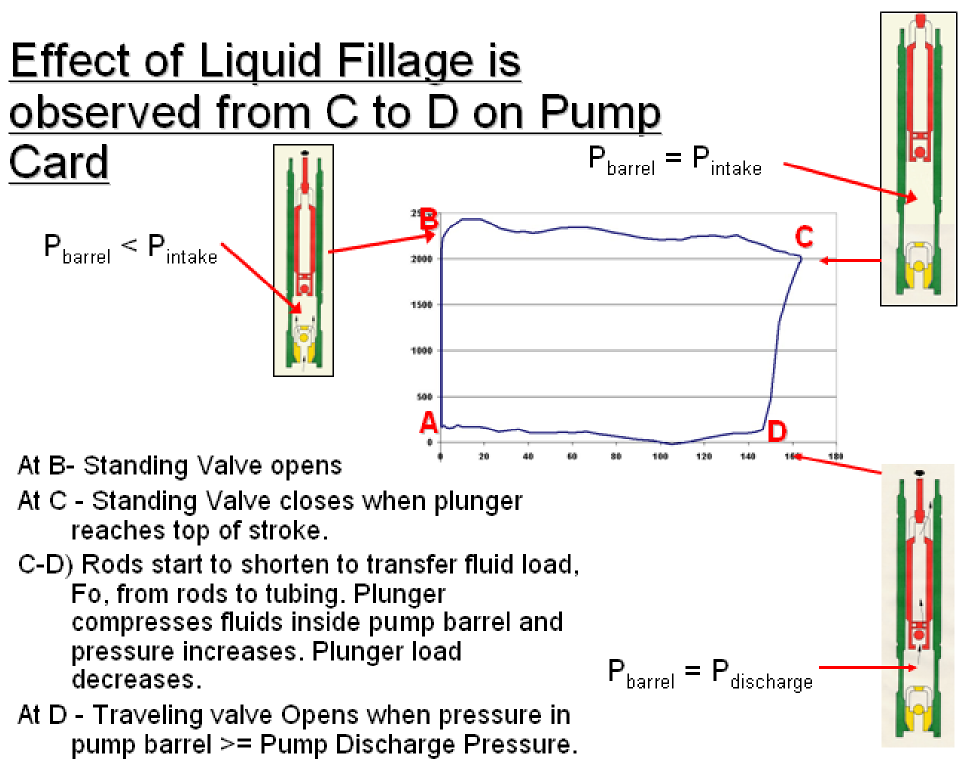

Figure 2 – Valve Status and Flow of fluid During Plunger Stroke

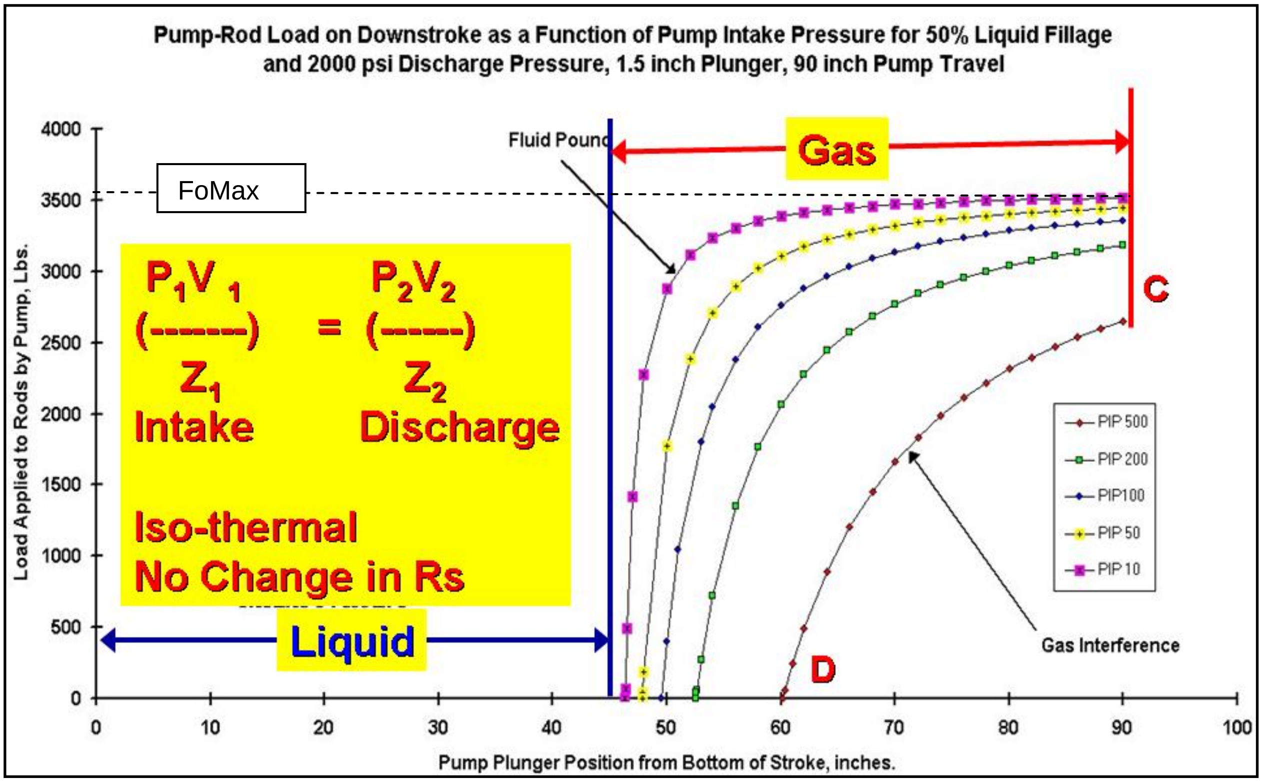

Figure 3 – Effect of PIP on Shape of Down stroke portion of Pump Dynamometer.

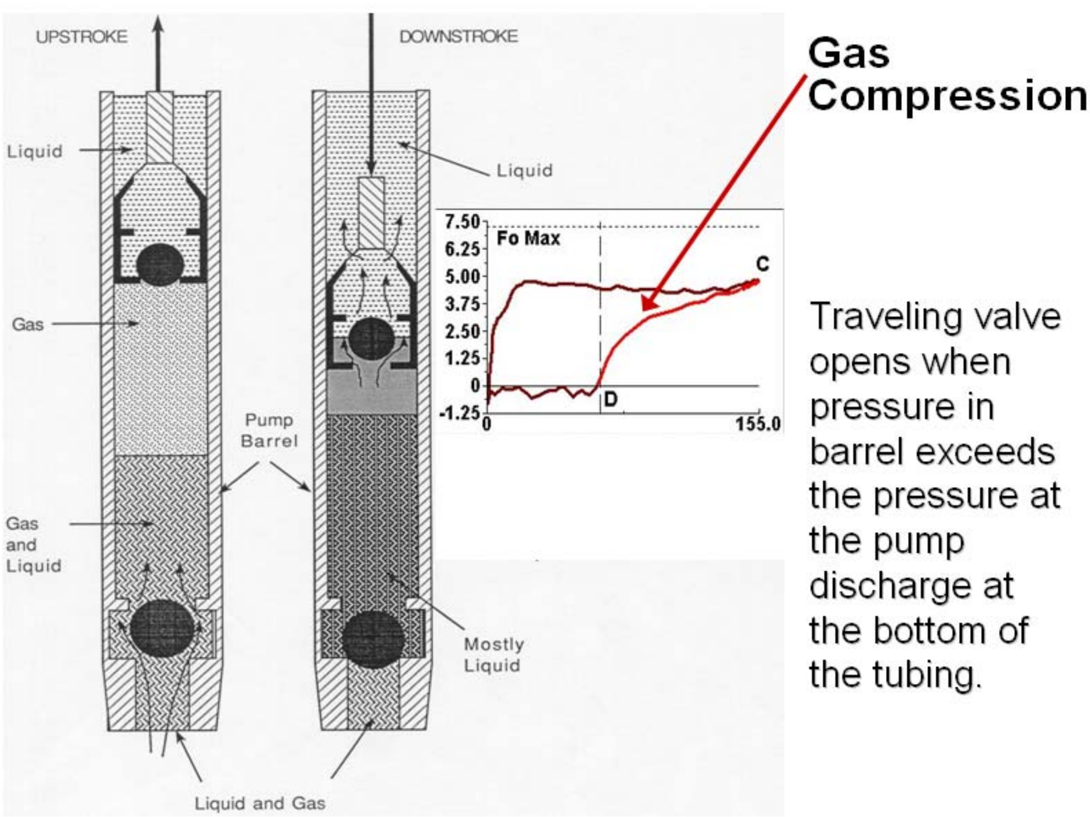

Figure 4 – Fluid Distribution in Pump with partial liquid fillage

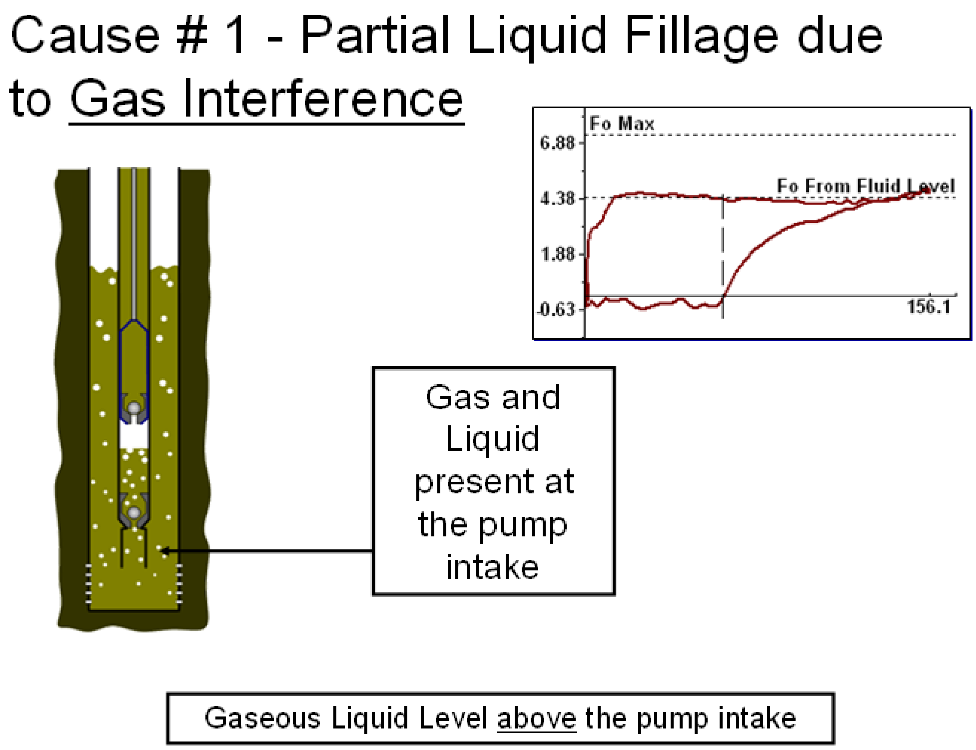

Figure 5 – Gas Interference Condition

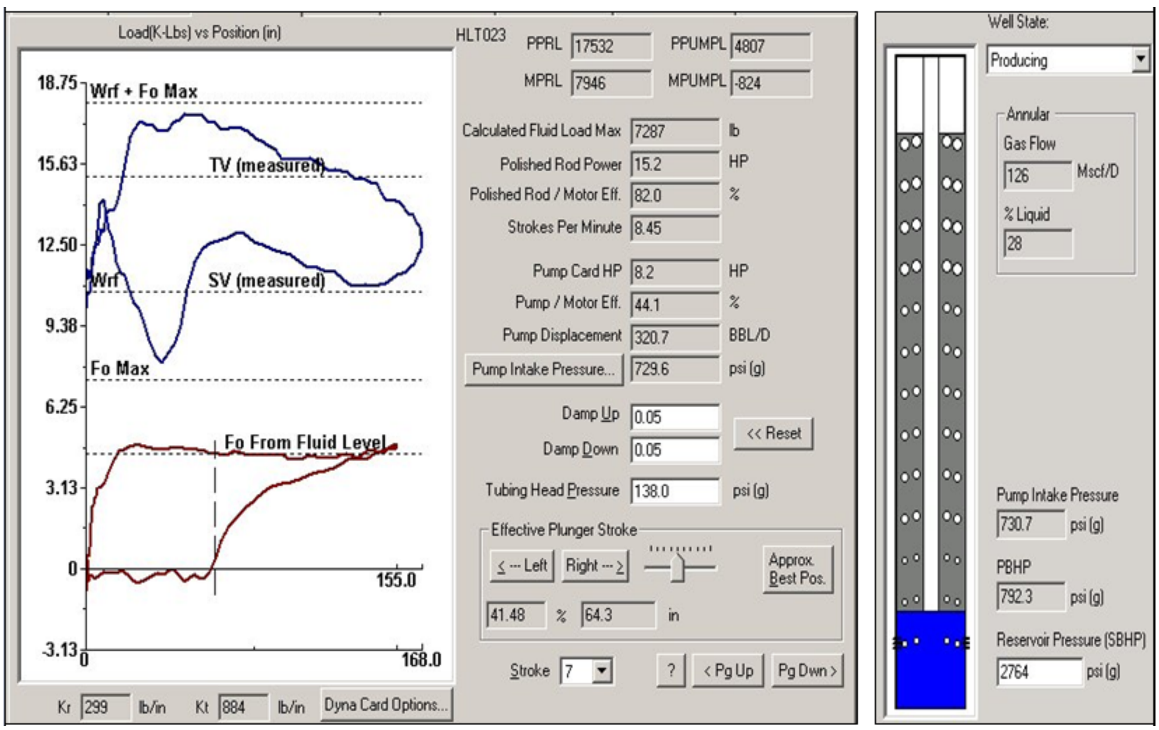

Figure 6 – Gas Interference: Incomplete Pump Fillage and High Fluid Level

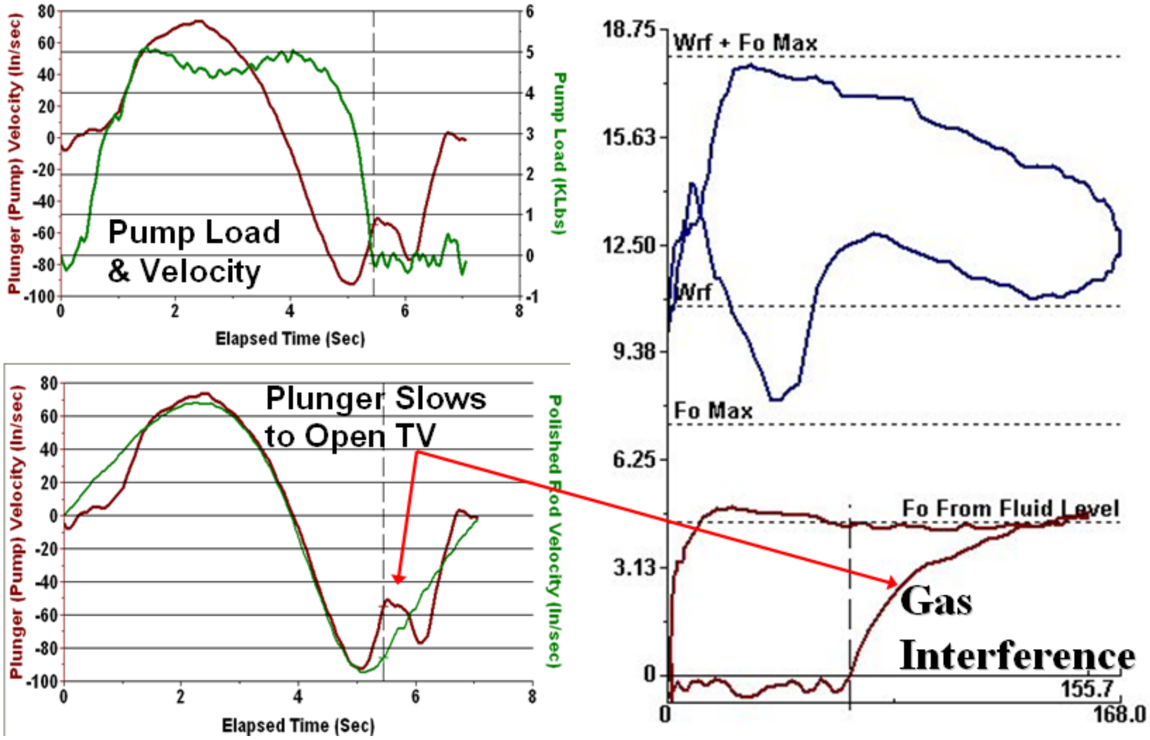

Figure 7 – Effect of Compression of high pressure gas on Plunger Velocity and Load.

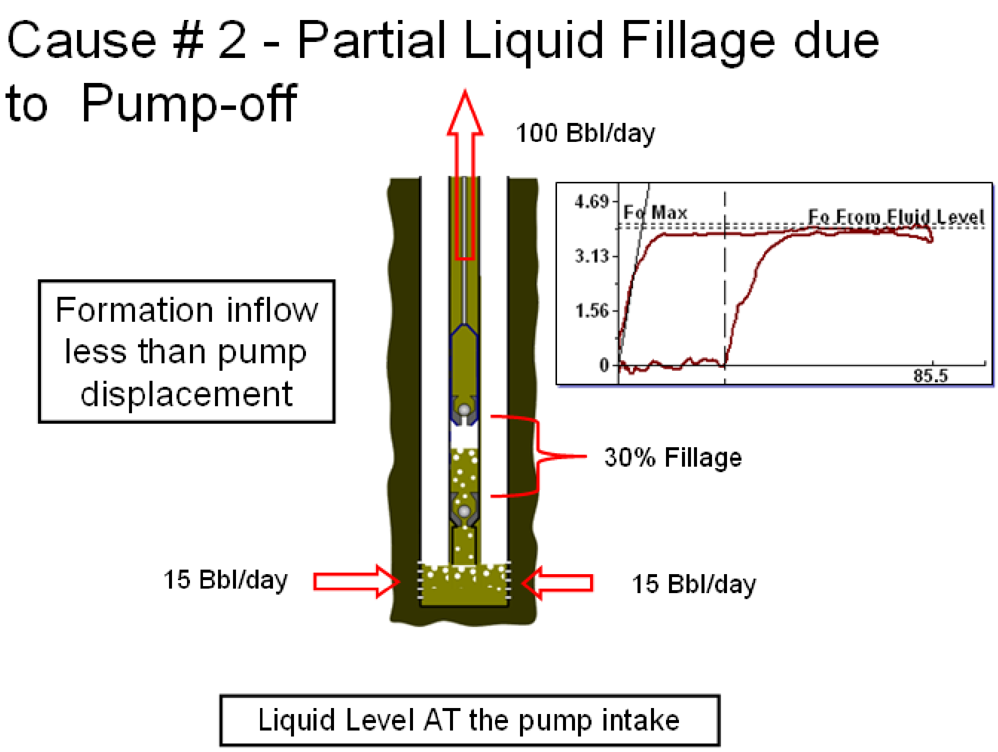

Figure 8 – Pump-Off Condition

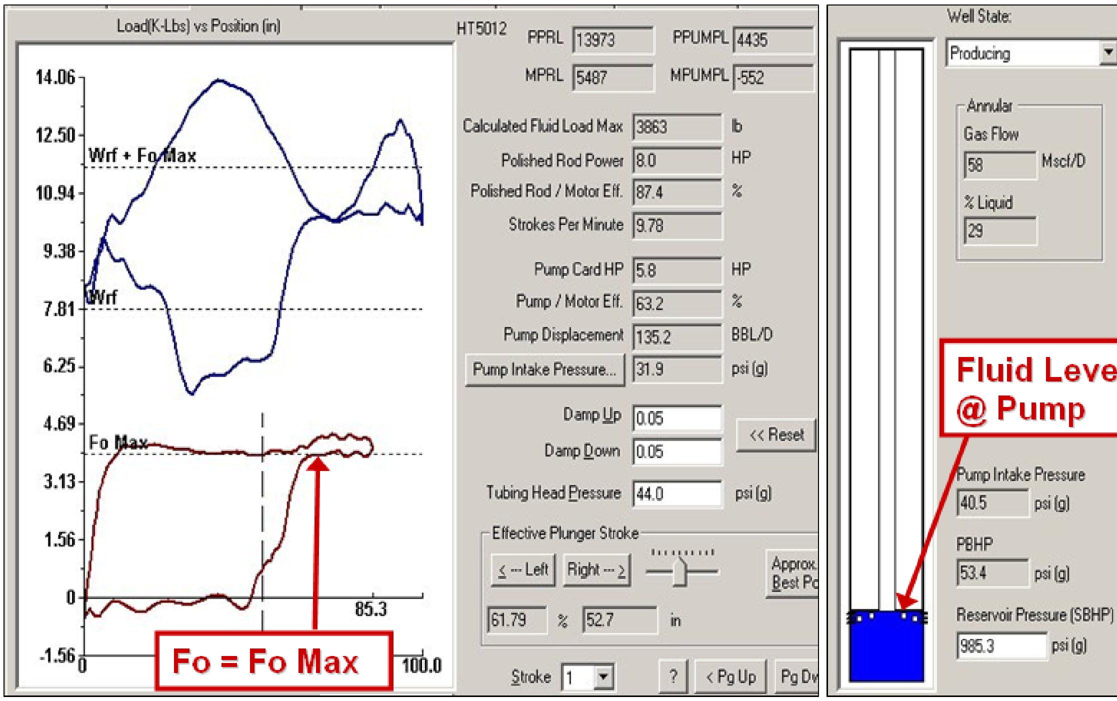

Figure 9 – Pumped off well with fluid level at pump intake

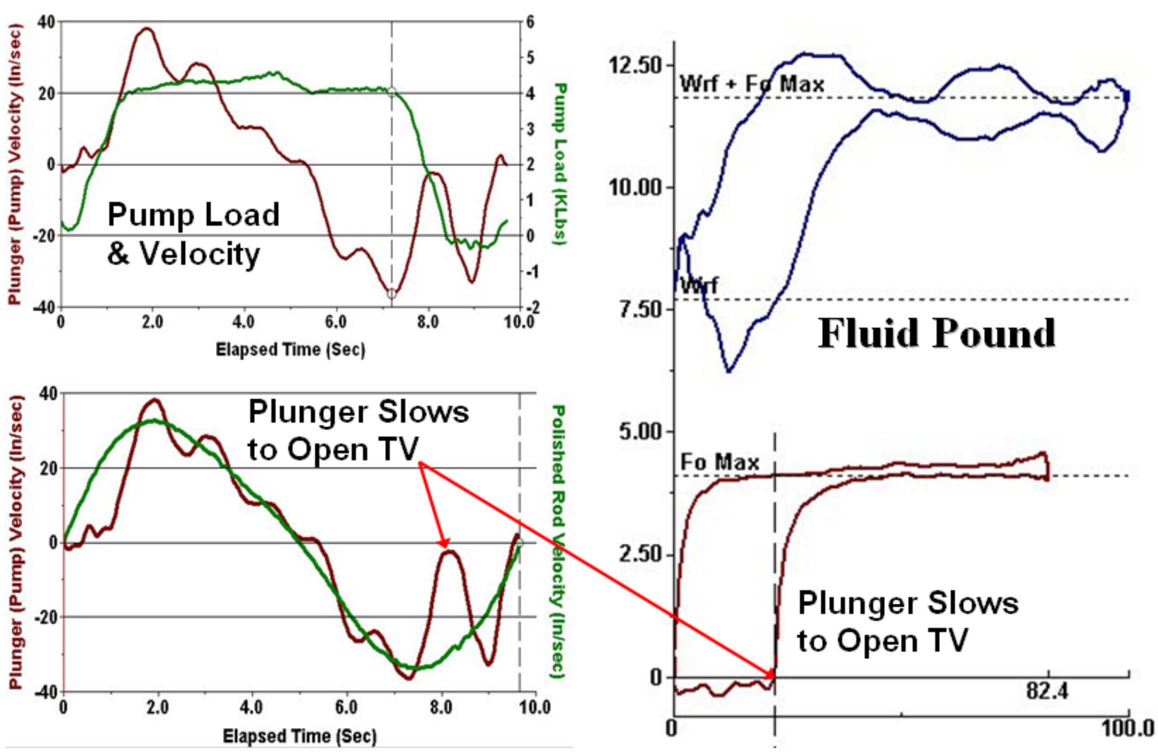

Figure 10 – Effect of compression of low pressure gas on Plunger Velocity and Load

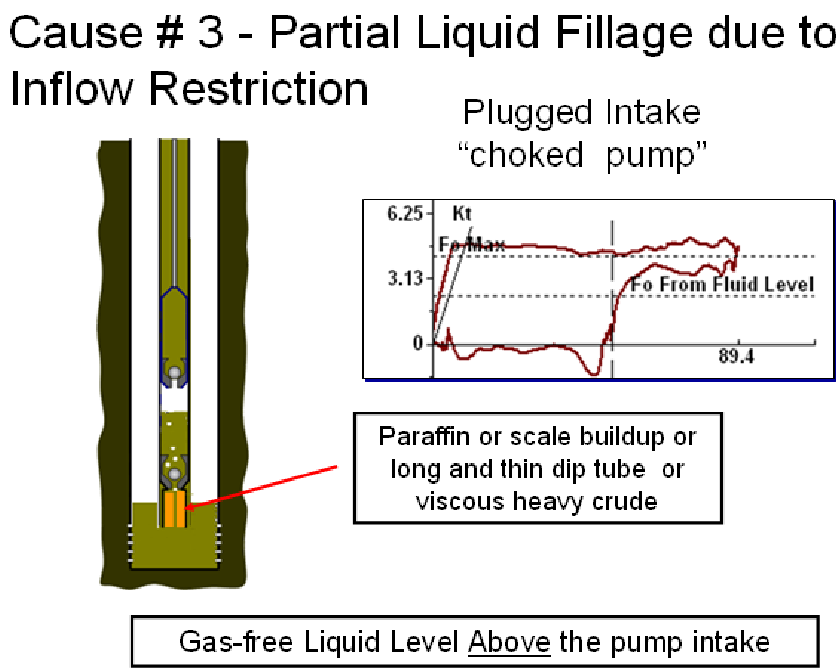

Figure 11 – Choked Pump Condition

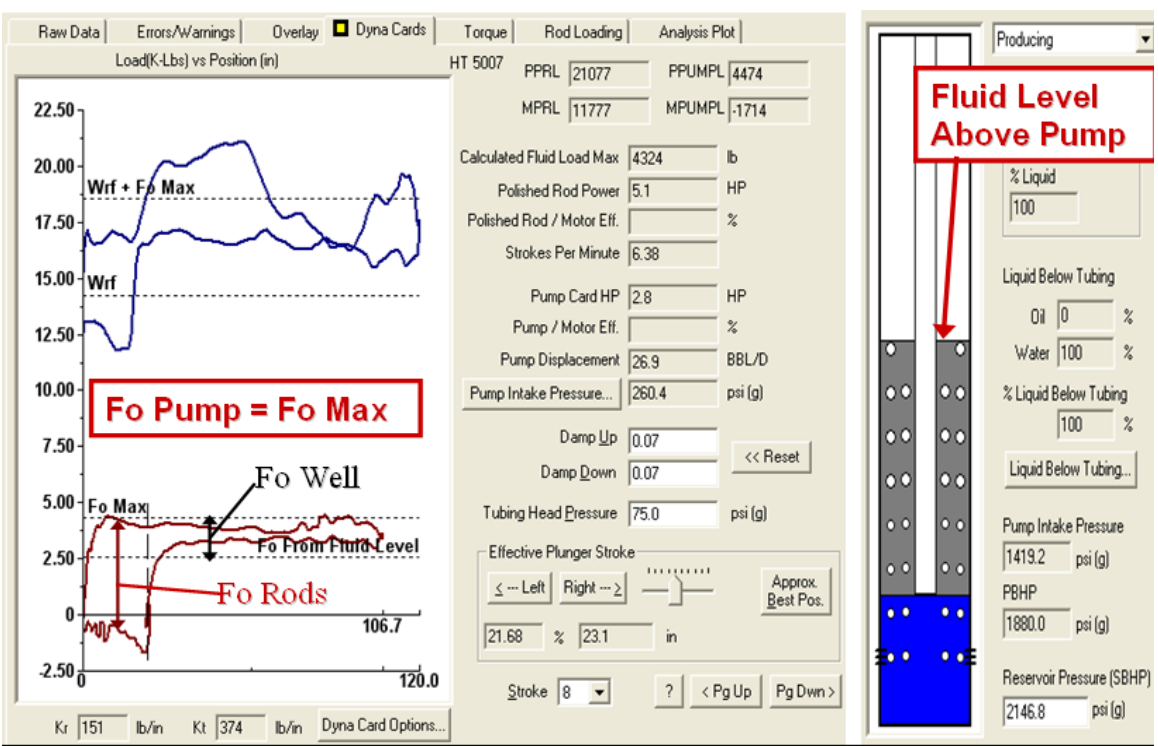

Figure 12- Well with plugged pump intake.

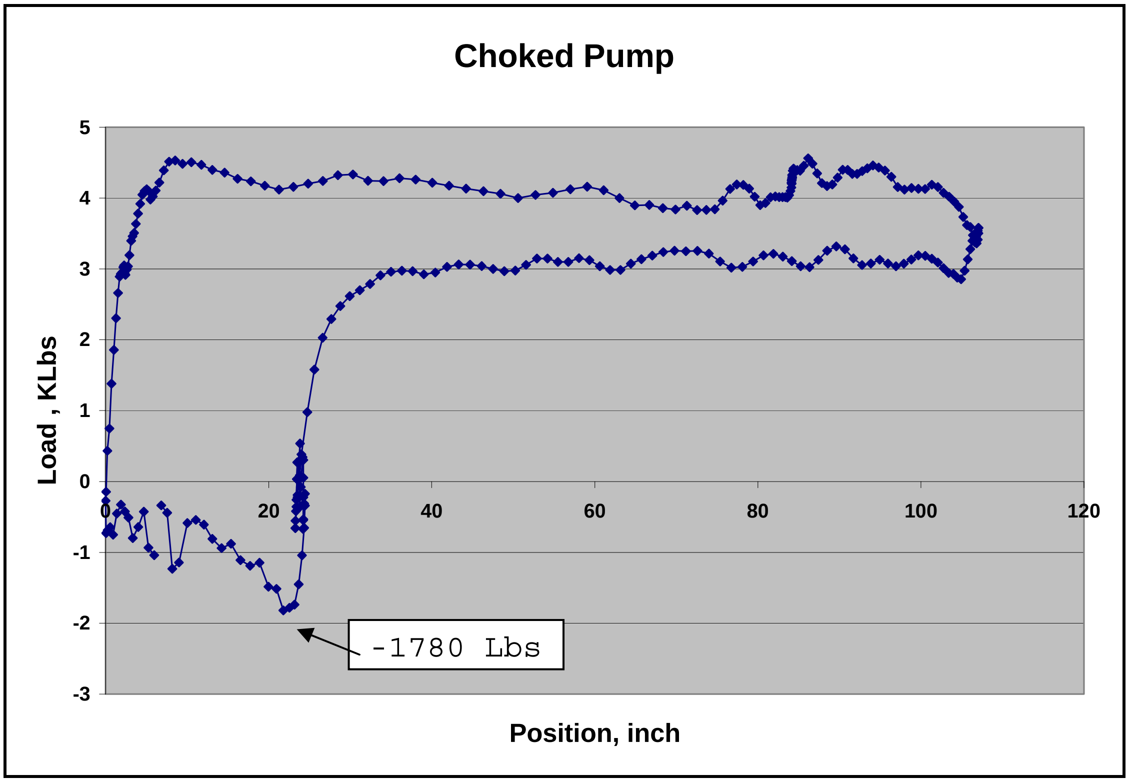

Figure 13 – Detail of Pump dynamometer for blocked intake

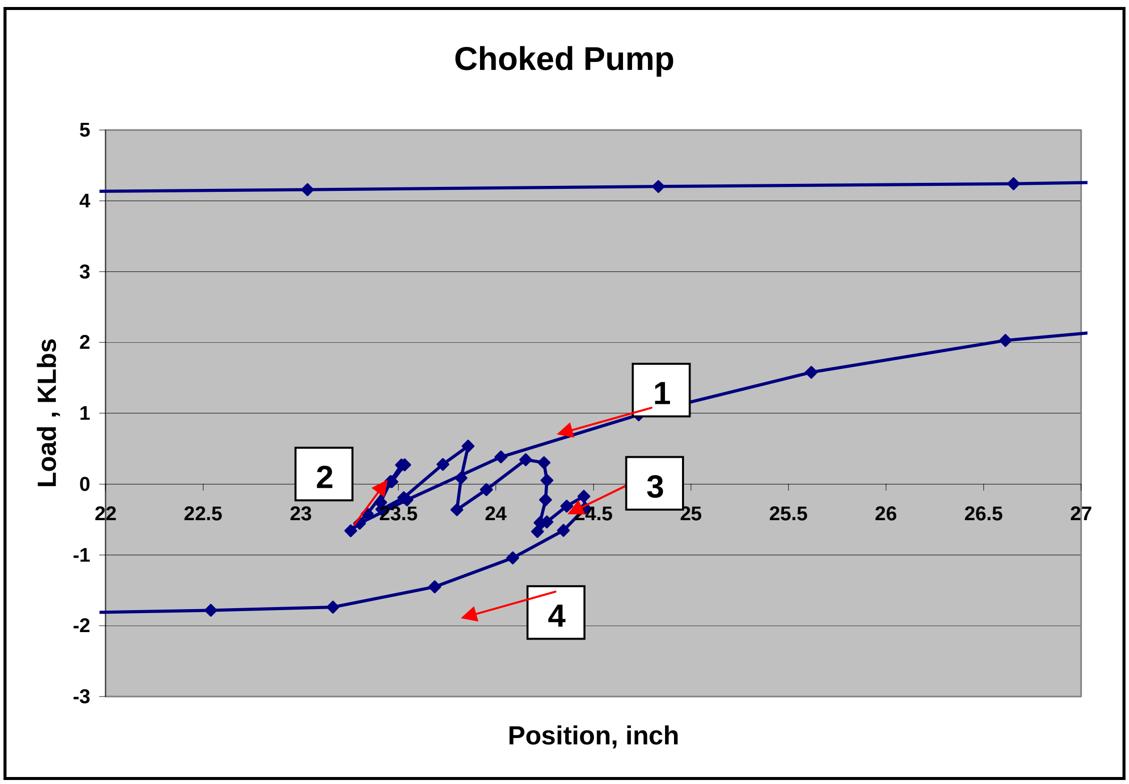

Figure 14 – Expanded view of downstroke

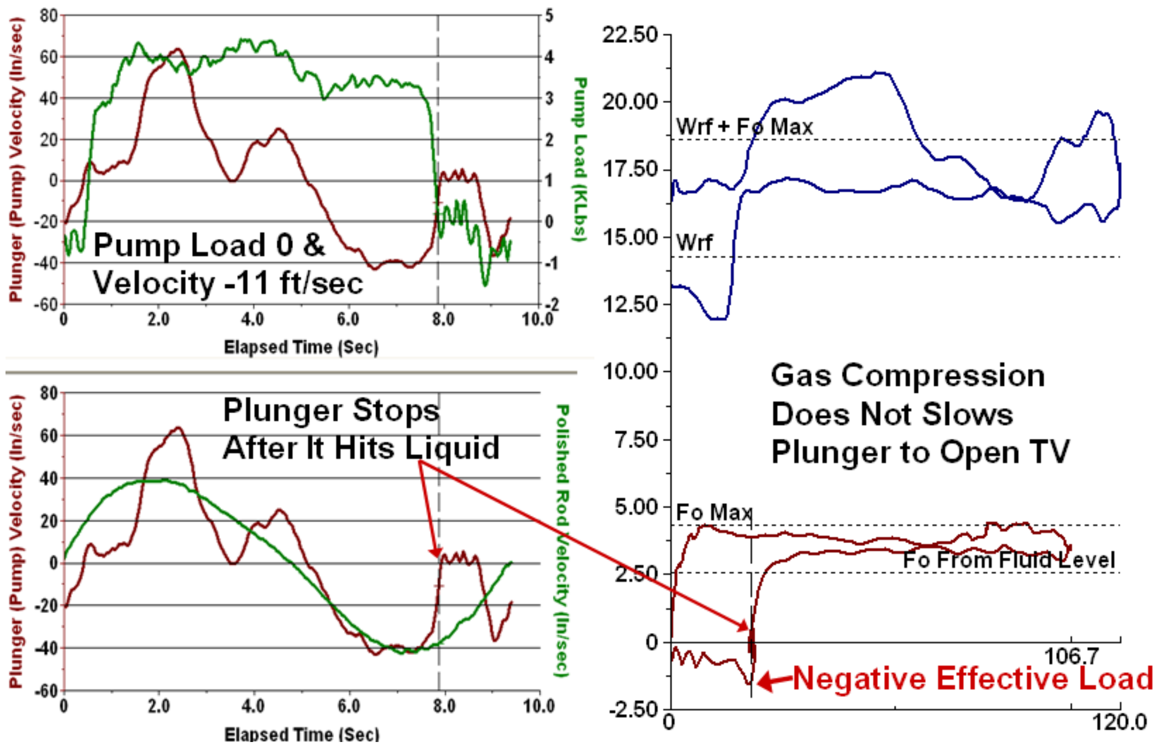

Figure 15 – Plunger velocity and loads for blocked intake

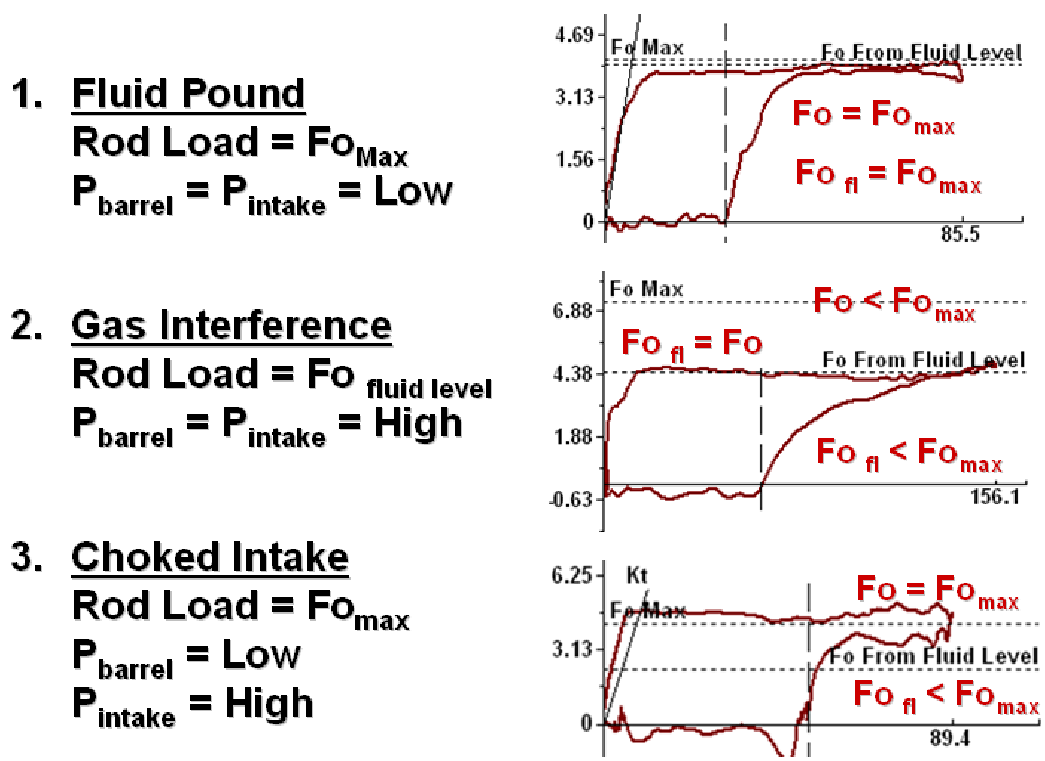

Figure 16 – Pump dynamometer characteristics of three causes of incomplete pump fillage and relationship to fluid level surveys.