PUMP CARD ANALYSIS SIMPLIFIED AND IMPROVED

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Surface dynamometer cards are very important in analyzing the performance of a rod-pumped well. The surface dynamometer card is a plot of load vs. position, during one complete stroke, for the load on the polished rod that is suspended from the pumping unit beam. An analysis of the surface dynamometer card indicates the loading on the beam, permits calculation of the axial stresses in the rods near the surface and permits calculation of the surface pumping unit efficiency by comparing the surface dynamometer card power to the pumping unit motor input power, and permits gearbox torque analysis when the counterbalance or counterbalance effect is known.

The loads and stresses in the rods throughout the rod string as well as the load on the pump plunger can be calculated, from the measured surface loads and polished rod position, using computers with proper software and proper interaction by the operator[1, 2, 3, 4, 5]. The position and movement of the plunger and sucker rods can be calculated along with the corresponding forces at all depths in the rod string. A pump card analysis allows the operator to determine the loadings on the pump plunger and hence determine the performance of the pump throughout its stroke. The pump performance can be analyzed to determine pump fillage, partial pump fillage, traveling valve and plunger leakage, standing valve leakage, sticking plunger, gas interference, pump intake pressure and other irregular pump conditions.

The interpretation of the pump card is simplified for the operator, if the pump card is considered to represent the load on the pump plunger as a function of plunger position. In other words, the pump card should represent the loads and position of the pump plunger as if the dynamometer measurement had been made by placing the load cell and the position indicator (accelerometer or string box) IMMEDIATELY ABOVE the pump plunger instead of at the surface with the downhole loads calculated at some place in the sucker rods, valve rod or sinker bars. The purpose of the diagnostic software (wave equation), when analyzing pump performance, should be to convert the loads and position measured at the surface polished rod to the actual load and position of the pump plunger during the pump stroke.

See figure 1 for an example of the construction of sucker rod pumps. This figure shows how the traveling valve and standing valve interact with the plunger movement to pump liquid from the well. On the upstroke, the plunger forces the liquid above the plunger towards the surface. The effective load on the connecting rod to the pump plunger is called F_o. Considering the plunger motion on the down-stroke, when the pressure below the plunger exceeds the pressure above the plunger, the ball in the traveling valve is lifted from the traveling valve seat. The load on the plunger at that moment is very close to zero except for the frictional forces between the plunger and the barrel and also the hydraulic forces that are necessary for the plunger to be pushed through the fluid in the pump barrel[6, 7]. Often, this compressive force on the plunger is small (in the 0 to 200 pound range). If the pump card is plotted in such a manner that the plunger load is plotted instead of the load in the valve rod, sucker rods or sinker bars above the plunger, the pump dynamometer card is much easier to understand and interpret.

The sucker rod pump is usually located near the bottom of the well inside of tubing. The tubing contains the liquids that are being forced to the surface. A 5000 foot well that has the tubing full of oil and water would have approximately 2000 PSI pressure surrounding the pump, valve rod, deep sucker rods and sinker bars. This hydraulic pressure along with the surface tubing pressure tends to compress steel sucker rods, fiberglass rods and other components of the rod string and pump. These hydraulic forces can be included or not included into the calculations of the forces on the downhole components depending upon the manner in which the operator desires to display the calculated loads. If the compressive hydraulic forces are included in the downhole load calculations, the loads are called true loads[8]. If the compressive hydraulic forces are not included, the loads are called effective loads[8].

The dynamometer pump card has been plotted in numerous ways over the years. Sometimes, the load on the sucker rod immediately above the plunger is used for the pump load. These loads may include or may not include downhole forces on the rods due to hydraulic load imposed by the fluids above the pump and the tubing pressure. Other so-called "pump cards" may be plotted as the load on the sinker bars immediately above the pump and might include or might not include the hydraulic forces exerted by the fluids in the tubing and the casing pressure.

Figure 2 shows some examples of so-called "pump cards". The top plot on the figure is the pump plunger load vs. plunger position. Note that the load on the downstroke is near zero, which represents the load on the plunger when the traveling valve is open. The middle card is an example where the loads are calculated in a ¾ inch sucker rod immediately above the pump including compressive forces on the sucker rod that are applied by the liquid in the tubing. Yet another so-called "pump card" is plotted at the bottom of the graph where the loads are calculated in a 1-½ inch sinker bar immediately above the pump including the compressive hydraulic forces that exist on the sinker bar. It is suggested that the card on the ¾ inch sucker rod be called a "3/4-inch True Load Sucker Rod Card". And, the card on the sinker bar should be called a "1 ½ inch True Load Sinker Bar Card". All of these downhole dynamometer cards are near the pump, but the true loads in rods near the pump do not represent the loads across the pump plunger.

Three substantial benefits exist for plotting the pump card as the load on the pump plunger; that is, the pump load is near zero on the down-stroke when the traveling valve is open. First, the calculated load on the pump down-stroke can be used as an aid in evaluating the accuracy and quality of the measured surface load and position data and the operator entered well information. Second, the calculated pump card load data on the up-stroke can be used to estimate the relative magnitude (high/medium/low) of the pump intake pressure by visual observation. Third, the pump card that shows downstroke forces substantially below zero and upstroke loads substantially above the load necessary to lift the liquids to the surface without help from the reservoir pressure indicates an undesirable anomaly, and the system should be studied further. The additional energy requirements shown by an oversized pump card (excessively low loads on the downstroke and excessively high loads on the upstroke) indicate low overall pumping unit system efficiency. If the extra power and load requirements are from paraffin or a tight stuffing box, then the well can be improved by treatment or rework. If the additional load requirements in the pump card are from a crooked wellbore and sucker rod drag, reduction of the extra loads and higher power requirements indicated by the oversized pump card is generally more difficult to accomplish.

The wave equation can be used to calculate loads at the plunger as a function of measured surface load and position data along with other well information. If compressive hydraulic forces are not included, then the calculated load at the pump card on the downstroke will be near zero when the traveling valve is open. If the measured surface load and position data are accurate, then the plunger load on the downstroke will be near zero except for the hydraulic forces necessary to push the plunger down through the fluid in the pump barrel plus any frictional forces that exist between the plunger and the pump barrel. If the surface downstroke load data is in error by 5% of the load cell range (typically 30K pounds), then the calculated downstroke pump card loads could be in error by more than a thousand pounds. Normal down-stroke friction for the plunger is small (0 to 200 pound). If the down-stroke plunger load is not near zero when the traveling valve is open, then the accuracy of the surface load and position data should be questioned and the load cell should be recalibrated and the electronics verified for accuracy. This analysis assumes that the mechanical frictional forces (such as stuffing box friction and sucker rod and paraffin drag) are minimal.

Dynamometer manufactures[9, 10] use the above concept to calibrate surface load data when qualitative load cells are used. Qualitative load cells have the advantage of easy, safe and rapid installation. When the surface load data is obtained, the maximum and minimum loads generally vary thousands of pounds relative to the average load. The shape of the surface card is correct and the change in loads is accurate, but the absolute values of the loads are not calibrated relative to zero. The average value of the load data can be any number (either positive or negative or even zero). The surface data can be used to calculate a pump plunger card. If the pump plunger card has an average value of minus 8,500 pounds on the downstroke when the traveling valve is open, then the surface data must have been approximately 8,500 pounds too low relative to the correct load cell zero. Thus, the surface data is adjusted by adding 8,500 pounds to each load value. This procedure has proven to provide dynamometer cards of sufficient accuracy for most dynamometer analysis[9, 10].

The standing valve test measures the buoyant weight of the sucker rod string if the standing valve is operating properly and friction between the rods and tubing are minimal. If the weight measured with an accurate load cell and electronics does not closely agree with the calculated buoyant sucker rod weight, then the data entered for the sucker rod string or the data entered for the fluid in the tubing is in error, (assuming a conventional well without crooked wellbore or other friction problems). The same test can be used when calculating the pump plunger card load. If the calculated plunger load on the downstroke is not a reasonable value for the well, then the well data or the measured loads obtained from the load cell and electronics should be checked. See Figure 3 and note the close values of the measured and calculated buoyant rod weight. Often, the values are even closer than these.

Donut load cells used in P-O-C operations are often installed without a centralizer or equalizing spacers on the top and bottom of the load cell. Often the accuracy of the load cell is not within 5 % of actual load. Equalizing spacers will improve the accuracy of the measurement. If equalizing spacers are not used on the top and bottom of the donut load cell, the donut load cell accuracy can often be improved by placing a rubber or plastic cylinder between the polished rod and the donut load cell to centralize the donut load cell on the polished rod. This centralizing of the load cell will improve the loading on the load cell and increase the accuracy of the load cell electrical output[11]. The cost is minimal. Load cells can also be damaged when the sucker rods "hang up", and then fall violently onto the load cell. Plotting the pump plunger card with respect to the zero load reference line helps to determine if the measured loads are as accurate as desired. Inaccurate pump plunger loads can be caused by the load cell not properly loaded, a damaged load cell or other electronic or cable problems.

The second reason for using a zero load reference line is that a second reference load line, $F_{O\ Max,}$ can be added to the graph. $F_{O\ Max}$ represents the load on the plunger for the plunger to lift the liquid to the surface, assuming no help from the reservoir pressure. The fluid load on the plunger during the up-stroke, when the pump intake pressure is at a minimum, is called $F_{O\ Max.}$ $F_{O\ Max}$ is the force exerted by the pump plunger on the upstroke to the liquids in the tubing that is necessary for the plunger to lift the liquids in the tubing to the surface assuming that the pump intake pressure is zero. This force can be calculated from plunger size, fluid characteristics, surface tubing pressure and other factors. This line should be plotted on the pump card along with the zero load line.

F_o is defined as the load on the plunger on the upstroke. Observation of the height of the pump card, F_o in comparison to the load $F_{o\ Max}$ indicates to the operator how much work is being applied by the pump to lift the liquids to the surface. F_o is defined as the actual load on the pump plunger that results from the fluid load in the tubing plus frictional forces less a positive force that is caused by the well pressure (pump intake pressure) that helps lift the fluids to the surface. The difference between F_o and $F_{o\ Max}$ is the force that the producing bottomhole pressure applies to the bottom of the plunger during the upstroke.

If the load on the plunger is approximately 80% of the F_{oMax} load, then the operator knows by observing the pump card diagram that the producing bottomhole pressure is supplying the other 20% of the load. This indicates the presence of significant backpressure against the formation and indicates that additional production is available from the well. If the pump intake pressure is near zero, then the plunger load on the upstroke will approximate the calculated $F_{O\ Max.}$

Figure 4 shows a surface dynamometer card and a pump plunger load card. The surface dynamometer card is a plot of measured polished rod load at various positions throughout the measured stroke. The pump card is a plot of the calculated loads on the pump plunger at various positions throughout its stroke. This is the plunger load that is applied to the pump valve rod or the bottom of the sucker rod string. The pump card shows that the down-stroke portion of the pump plunger card is near zero. This indicates that the surface load and position data and the well information data are reasonably accurate. The load on the downstroke being near zero also indicates that excessive stuffing box friction, sucker rod drag or other downhole friction problems are not present.

The lower graph is the calculated pump plunger card with F_{oMax} value shown on the plot. The operator can simply observe the card and determine that the pump is partially filled with liquid and that the pump intake pressure (producing bottomhole pressure) is low because the plunger load, $Fo_,$ on the upstroke is slightly less than $F_{oMax.}$ The pump is supplying most of the power necessary to lift the liquids to the surface. The reservoir is supplying very little of the energy necessary to lift the liquids to the surface. The producing bottom hole pressure is low. The well file data shows that the tubing is not anchored and the tilted card to the right also indicates that the tubing is not anchored.

The pump card on the upstroke can be compared to the traveling valve test. The pump card on the up-stoke indicates the load on the pump plunger just as the traveling valve test indicates the fluid load on the upstroke that is in excess of the buoyant weight of the sucker rods. See Figure 5 that shows a comparison of F_o obtained by a traveling valve/standing valve test and F_o obtained from a pump card.

Another advantage exists when the pump card is plotted as the plunger load and plunger position. The compressive forces necessary to push the plunger and traveling valve down through the fluid in the pump barrel are shown on the pump card. These compressive forces help to determine the amount of sinker rods or larger diameter sucker rods that are desirable to prevent the lower sucker rods from being in compression and riding against the tubing as the lower sucker rods push the plunger down through the liquid in the pump barrel. Sand and debris can accumulate between the plunger and pump barrel and cause the plunger to drag against the pump barrel as the plunger is forced downward. A compressive force on the plunger of 250 pounds would require more sinker bars (or larger sucker rods immediately above the pump) than a compressive force of 50 pounds on the plunger.

When calculating a pump card showing plunger load using measured surface load and surface position data, the surface load and position data must be accurate for the loads on the pump card to be accurate and meaningful for determination of downhole compressive forces on the plunger. For example, if the surface load on the downstroke is in error by 1000 pounds, then the pump load will be in error by approximately 1000 pounds. Numerous laboratory and field tests show that a donut type load cell that does not have spherical centering washers above and below the load cell can have errors in excess of 30%. For a 30,000-pound load cell to be satisfactory to measure surface load data that will result in meaningful calculated pump plunger card data, the accuracy of the load cell, cables and electronics should be about 0.1 % or +- 30 pounds. Many load cells, cables and associated electronics do not have the precision for calculation of accurate pump plunger cards. Often times, the so-called pump card may intentionally be plotted as a True load sucker rod card (with compressive fluid forces) where the minimum and/or maximum expected loads are not known by the analyst, so that the error in the load cell or in the electronics is not obvious to the analyst.

The pump plunger card is calculated from the surface load and position data, the sucker rod string information and the fluid properties. Unaccounted friction errors can occur in the calculated pump card due to a tight stuffing box, unknown or incorrectly assumed damping forces, paraffin, sucker rod box friction, a crooked wellbore and other factors. The pump card analyst must be aware of these possible unknown forces when interpreting the card. See Figure 6. When the pump card upstroke load extends above the F_{oMax} line and the downstroke load is below the zero load line, the oversize (excessive load range) pump card indicates low efficiency in the pumping system. Paraffin, a crooked wellbore, wellbore friction, excessive stuffing box friction and a poor design of the rod string can cause an oversized pump card and poor efficiency. The cause of the oversized pump card should be determined in an effort to improve system efficiency.

Examples of pump plunger cards and sucker rod cards are shown to illustrate the additional visual analysis that is available with the pump plunger card plotted in conjunction with the zero load line and the F_{oMax} reference line.

Figure 7A shows the surface dynamometer data with a pump plunger card. The pump downstroke load shows that the measured dynamometer data and the well data are probably accurate. Excessive drag on the downstroke does not exist. The rounded top on the pump card indicates that the plunger or traveling valve leaks some on the upstroke. The pump plunger load on the upstroke indicates that the producing bottomhole pressure is low because the upstroke load is near $F_{oMax.}$ Figure 7B shows another example of a leaking traveling valve or plunger. The plunger load on the upstroke is considerably less than $F_{oMax.}$ The leak is so severe that all of the available production is not being removed from the wellbore because an excessive producing bottomhole pressure exists that restricts production.

Figure 8 shows a pump card that indicates that the measured data and well data are probably accurate. The upstroke load indicates that the producing bottom hole pressure is low. The pump is approximately 50 % full of liquid during the normal pumping cycle.

Figure 9 shows a pump card that indicates that the measured data and well data are probably accurate. The upstroke load is much less than F_{oMax} indicating that the producing bottomhole pressure is restricting production from the reservoir. Gas interference is causing partial pump liquid fillage and restricts production.

Figure 10 is a well with fiberglass rods. The pump card shows that the rods are tagging at the end of the downstroke with a force of over 2000 pounds. This will cause damage to the rods and entire pumping system. The severe load change from the downhole compressive force is shown by the circled data on the surface card. This card was acquired with a high sampling rate of 240 samples per second to cause more accurate measurement and calculation of short time shock loadings.

The upper pump card in Figure 11 indicates a substantial 5000-pound reduction in load before the end of the upstroke due to an enlarged pump barrel to reduce gas lock problems. The downstroke load indicates that the measured data and well data are probably accurate. Some compressive forces exist on the downstroke that might be caused by double traveling valves or some other drag. The upstroke load indicates that substantial bottomhole pressure exists, and that additional production is available from the well. Note that the true load sucker rod card shown at the bottom of the graph does not permit the more detailed analysis.

Figures 12A and 12B show surface and pump cards on a well with the sucker rods parted from the pump plunger. Figure 12A, showing effective loads, indicates that the sucker rods are parted very near to the pump. (Or, the traveling valve could be stuck open.) Figure 12B, (with compressive forces shown on the pump card) does not allow the operator to visually estimate the depth of the sucker rod part.

Figures 13A and 13B are dynamometer cards on a well that has intermittent traveling valve operation. Figure 13A shows the pumping system in proper operating condition. Figure 13B show the surface and pump card when the traveling valve did not seat. The pump card shows that the failure is at the pump and that the traveling valve is not properly closing on the seat.

CONCLUSIONS

Plotting a pump card as the effective load on the plunger simplifies analysis, allows checking of measured surface loads and also allows direct and easier interpretation of the actual downhole forces for a more compete and better understanding of the pumping system, especially the pump performance.

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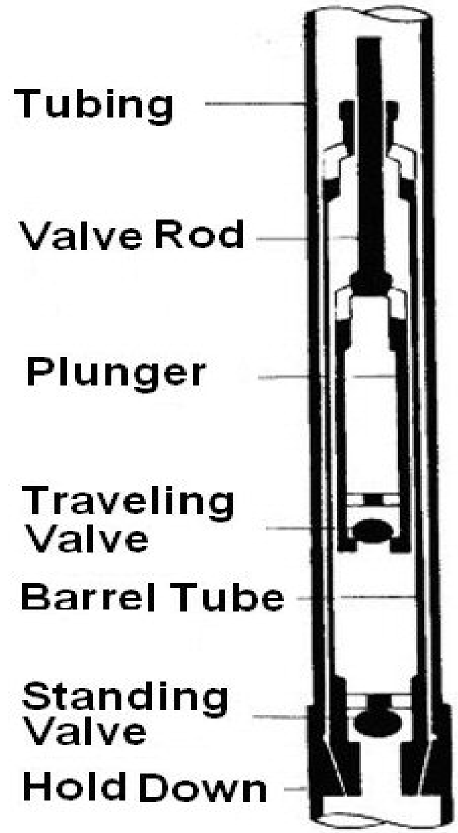

Figure 1 - Basic Parts of API RHB Pump

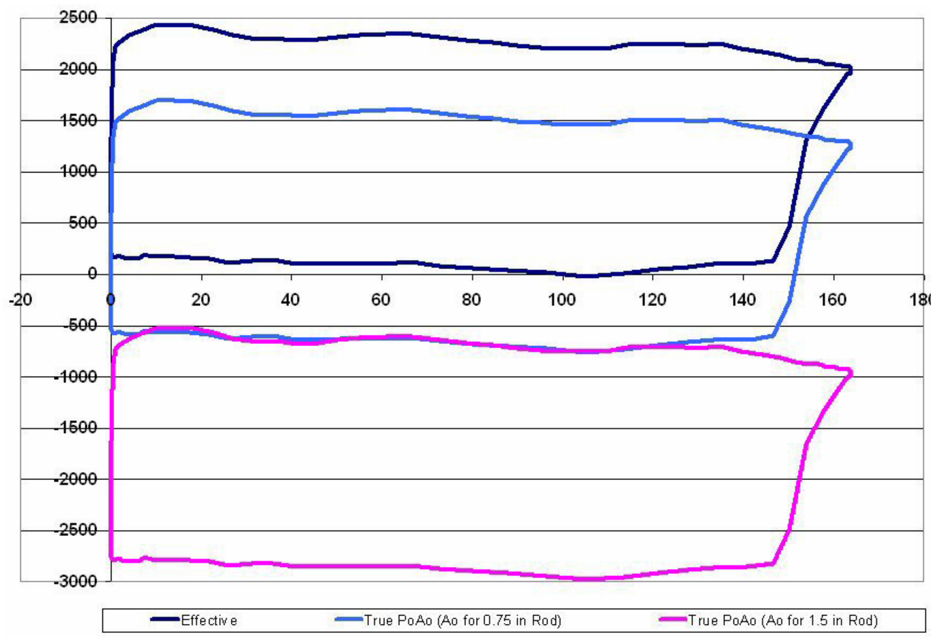

Figure 2 - Pump Plunger Card, ¾ inch True Load Sucker Rod Card and 1.5 Inch True Load Sucker Rod Card

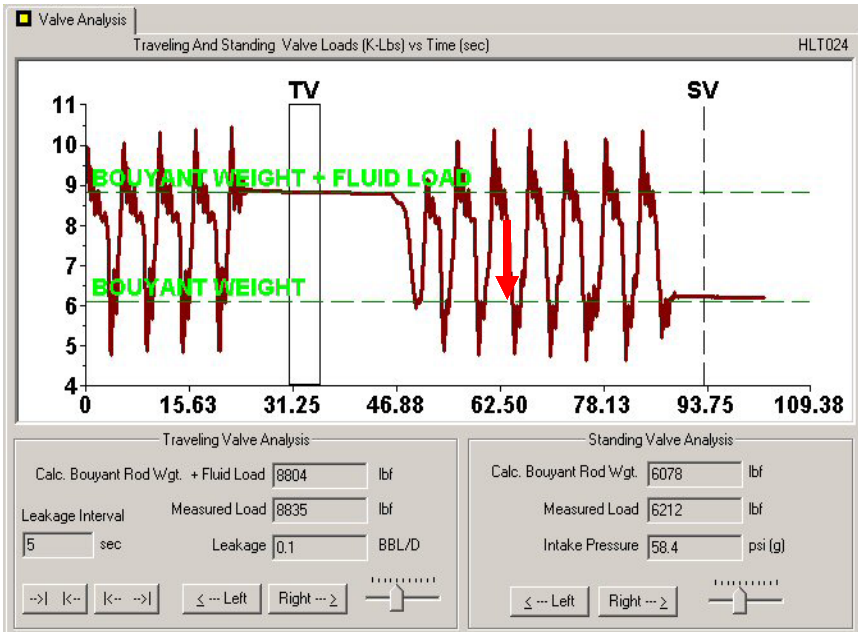

Figure 3 - Standing Valve and Traveling Valve Tests

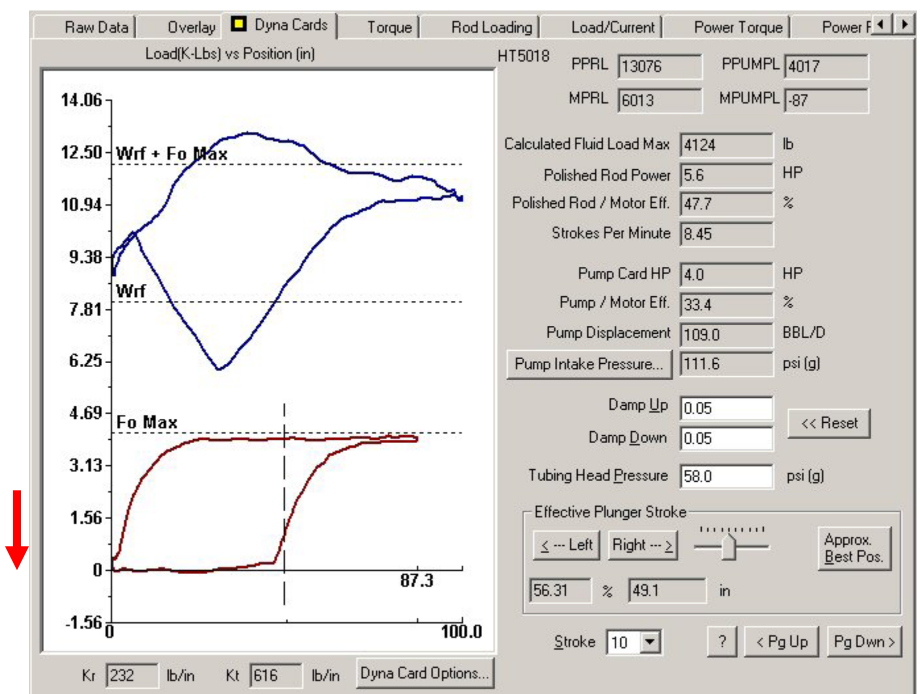

Figure 4 - Surface and Pump Plunger Dynamometer Cards and Analysis

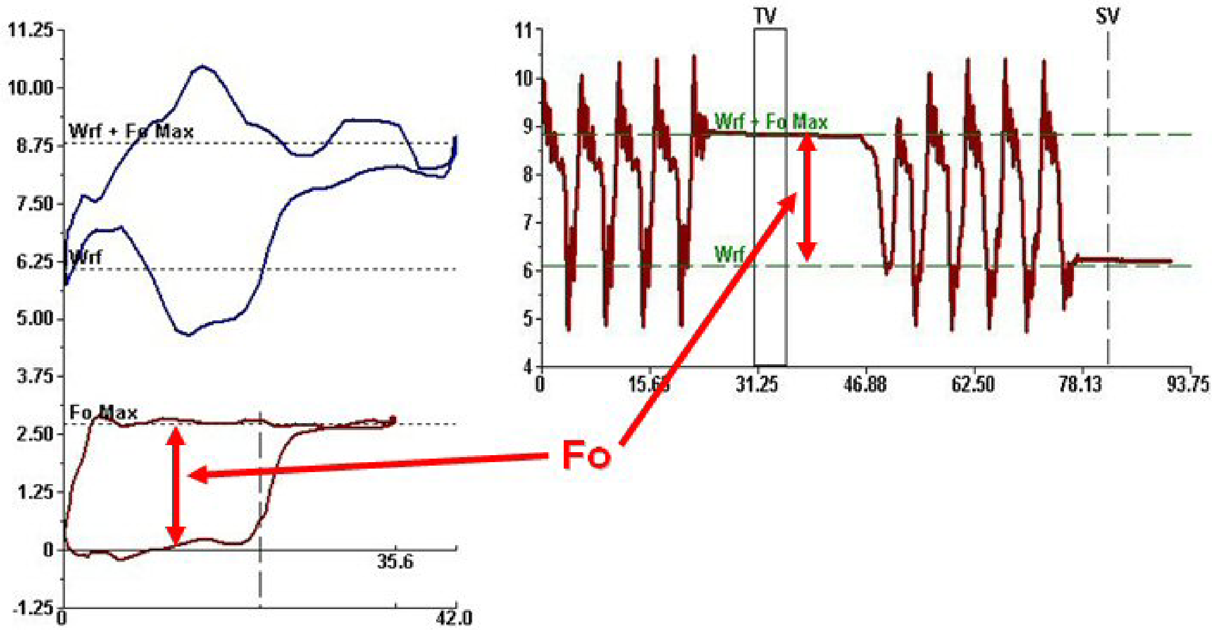

Figure 5 - Comparison of F_o from TV/SV Tests and Calculated Pump Card

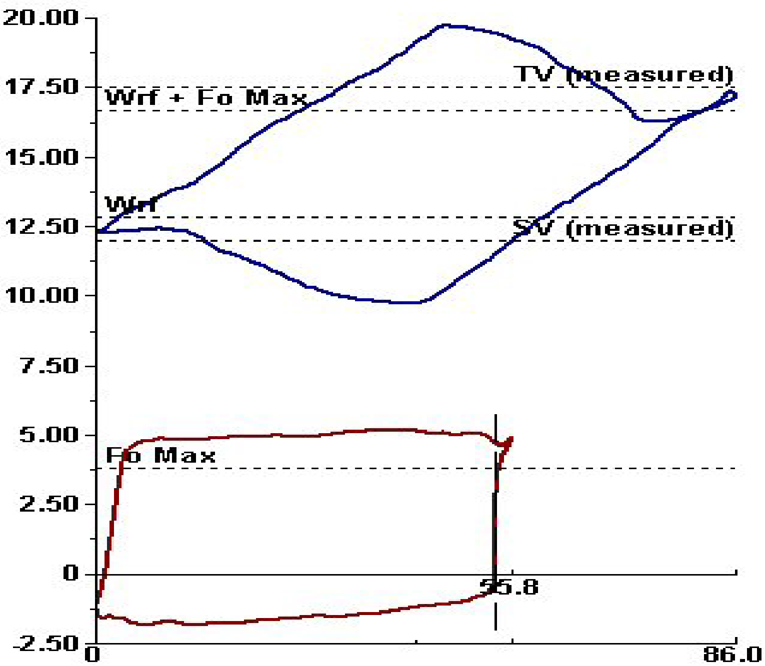

Figure 6 - Pump Plunger Card with Unaccounted Friction Showing Low Efficiency System

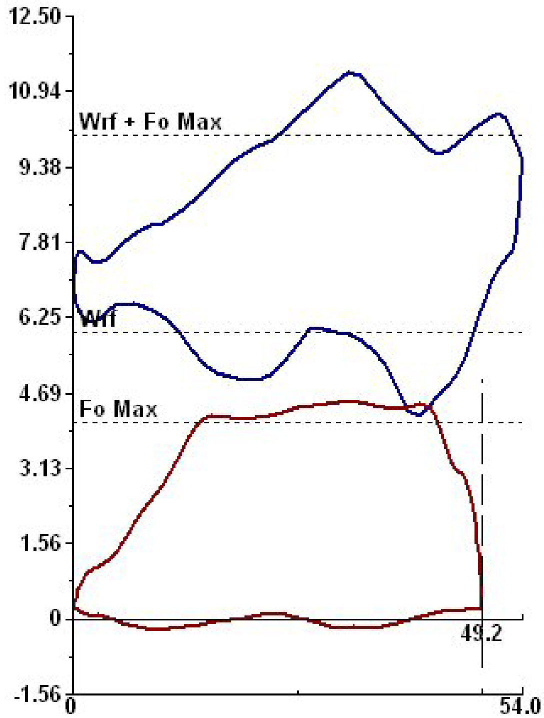

Figure 7A - Pump Card Showing Leaking Traveling Valve and Low Producing Bottomhole Pressure

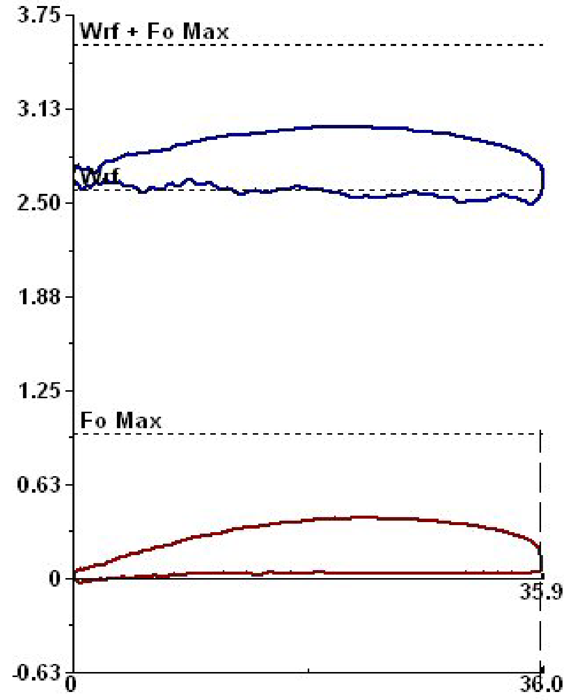

Figure 7B - Pump Card Showing Leaking Traveling Valve and High Producing Bottomhole Pressure

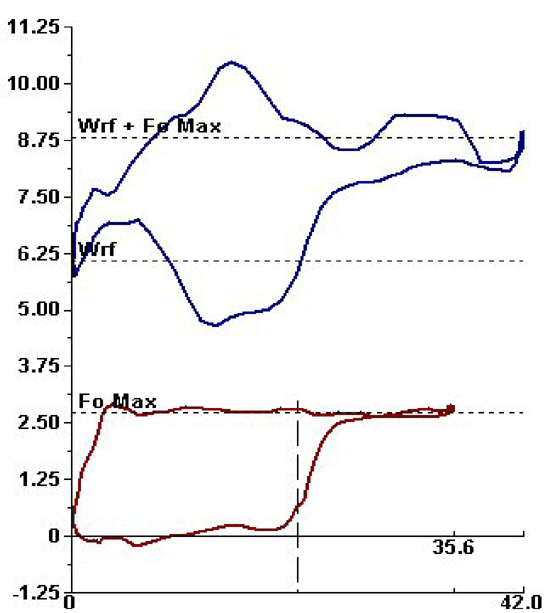

Figure 8 - Pump Card Shows Partial Pump Fillage with Low Producing Bottomhole Pressure

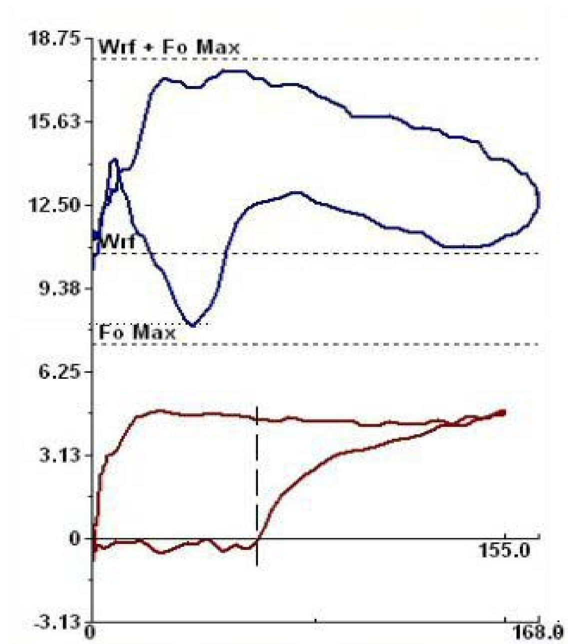

Figure 9 - Shows Partial Pump Fillage with High Bottomhole Pressure

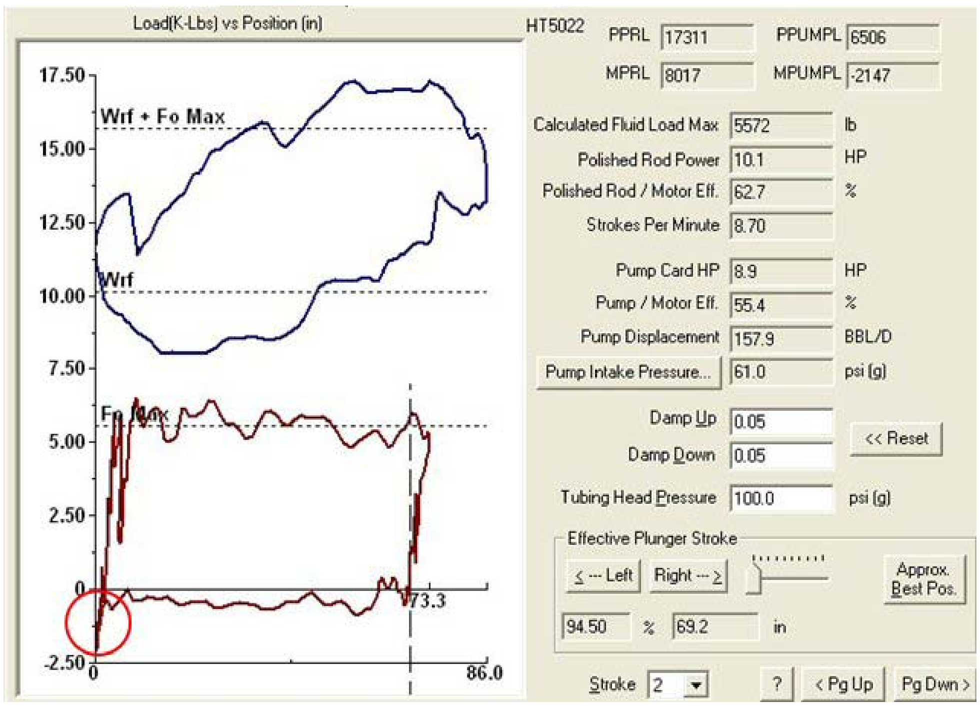

Figure 10 - Shows Fiberglass Rods Tagging Bottom with a 2000 Pound Force

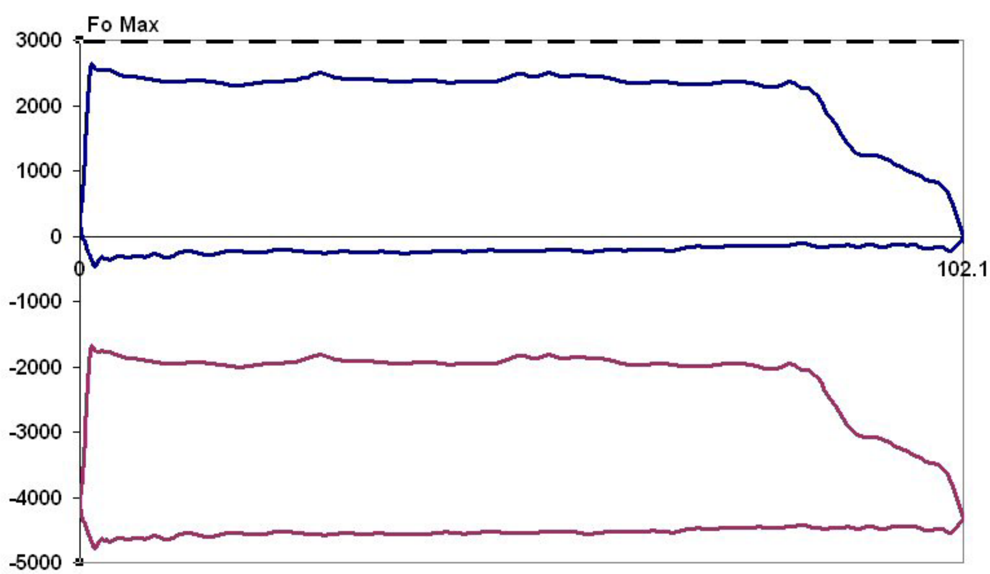

Figure 11 - Shows a Pump Plunger Card and a Sucker Rod Card on a Variable Diameter No-Gas-Lock Pump Barrel

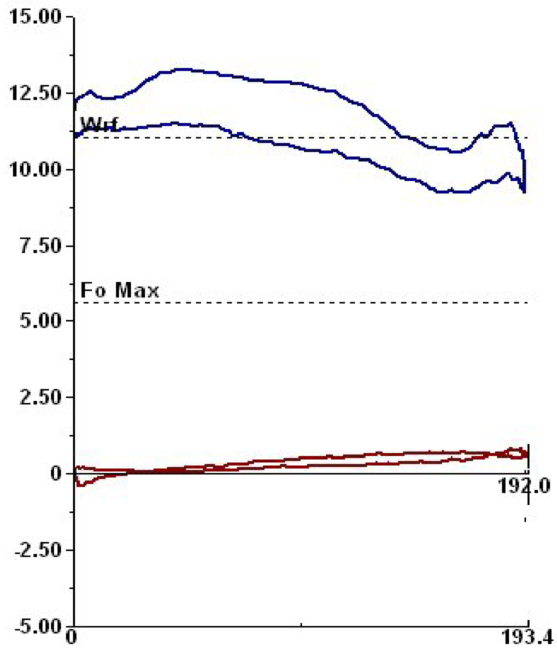

Figure 12A - Shows a Pump Card Part

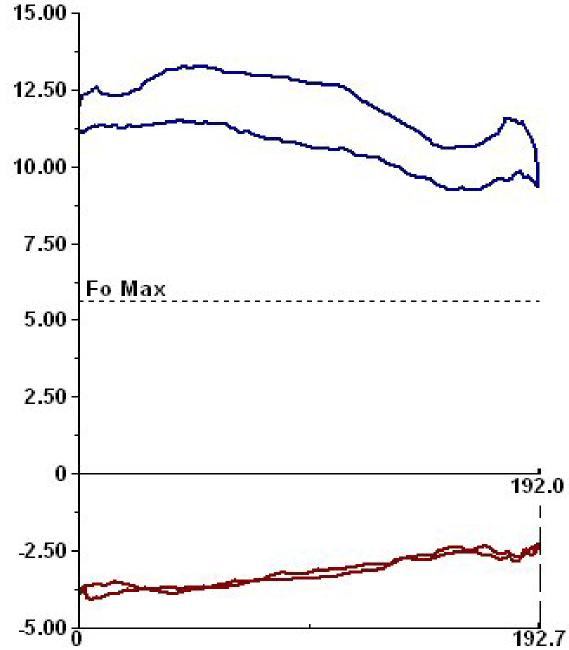

Figure 12B - Shows a True Load Having a Deep Rod Card Having a Deep Rod Part

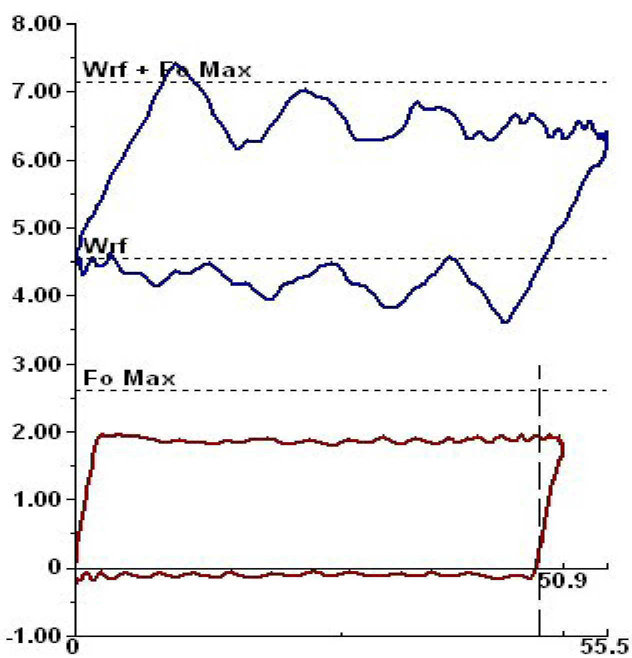

Figure 13A - Pump Plunger Card on A Well with the Traveling Valve Operating Normally

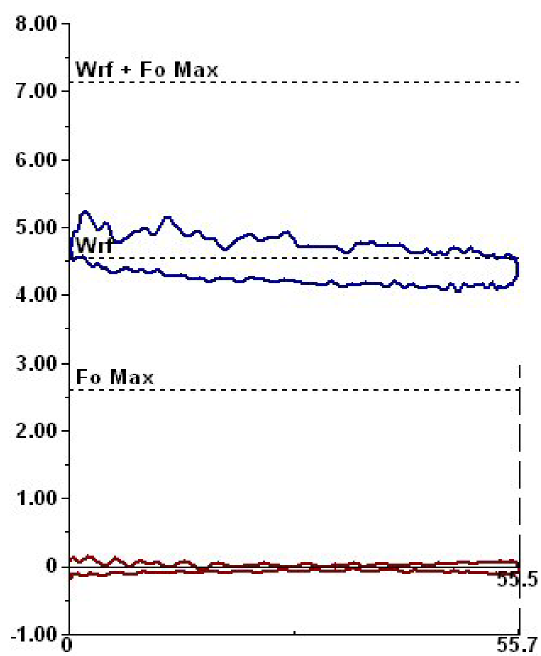

Figure 13B Pump Plunger Card On a Well with Trash Holding the Traveling Valve Off the Seat