ANALYSES OF LABORATORY, INSTRUMENTED SUCKER-ROD PUMP DATA

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ABSTRACT

A full-scale, transparent, laboratory, instrumented sucker-rod pump has been constructed to aid in designing a downhole, instrumented pump. The laboratory pump has demonstrated that key to the understanding of sucker-rod pumping is compression-chamber pressure. Laboratory data will be used to demonstrate real-time analysis techniques that will be used with the downhole, instrumented pump to differentiate between a gas-locked or a pumped-off well using compression-chamber pressure. For a gas-locked well, the pressure is symmetric between the upstroke and downstroke; where as, for a pumped-off well there are high and low pressure plateaus when the valves are open. A method will be demonstrated to determine sucker-rod pump fillage by cross plotting $(\text{Pressure})^{-1/\gamma}$ versus stroke (g is the heat capacity ratio). The intercept of the compression line and stroke gives pump tillage. The intersection of decompression and discharge pressure can be used to determine the residual gas trapped between the standing and traveling valves at the end of the downstroke.

INTRODUCTION

Although sucker-rod pumps are installed in nearly **90%** of all artificially lifted oil wells in the United States and have been widely used for decades, there are many issues regarding their performance that are not well understood. This is due to the difficulty of simulating wellbore conditions in the laboratory and of obtaining downhole data for a standard sucker-rod pump. Many persistent sucker-rod pump problems including partial pump fillage, gas interference, gas locking, fluid pound, sticking valves, rod compressional loading, equipment failure, reduced production, etc. are difficult to diagnose from the surface. In current practice, pump performance is inferred by measuring stroke and load at the surface and then calculating a downhole dynamometer-card. It would be advantageous to be able to predict pump problems rather than to simply diagnose them after they occur. To predict pump problems, it is necessary to have a better understanding of downhole pump performance.

In the past few years, new information about pump operation has been obtained by using downhole dynamometers. Additionally, recent numerical modeling of pump performance has provided added insight into some pump problems, while at the same time, raising questions about other issues, such as, gas breakout and compressional loading due to viscous drag. Many questions about pump performance remain.

The purpose of the project is two fold: first, instrument a pump in a lab, and then, based on that experience, develop a downhole, instrumented pump. By comparing downhole dynamometer cards (calculated from surface data) to data from instrumented pumps, methods for diagnosing and predicting sucker-rod pump performance can be improved. This paper reports the progress that has been made in analyzing laboratory compression-chamber data during the time when both valves are closed. Also discussed are techniques that have been developed for determining in real-time pump fillage and gas locking using compression-chamber pressure -- the pressure within the pump barrel.

Measurements made with the laboratory pump have demonstrated that the key to improving our understanding of sucker-rod pumping is to measure the compression-chamber pressure. Another important parameter in sucker-rod pump performance is dynamic pump spacing (the dead space or space in a pump not swept by the plunger). Thus, the downhole, instrumented pump has been designed to measure internal pump pressures and pump spacing, both un-known from surface measurements.

A full-scale transparent pump has been constructed by Harbison-Fischer and installed in the University of Texas closed-loop test stand. The test stand is six stories high and allows visual and instrumented study of pumping conditions. It has a standard pump jack, dynamometer, transparent casing and tubing, clear test-fluids with a range of viscosities, and the means to introduce air into the well to simulate natural gas. The transparent pump has been instrumented to measure the pressure profile throughout the pump while it is stroking. The transparent pump and clear fluids allow visual measurements and observations to confirm the interpretation of instrument readings. A video camera has been installed that moves up and down with the plunger. Tests have been conducted recording pressures and loads under a variety pumping conditions including a range of pump rates and fillage.

DOWNHOLE INSTRUMENTED PUMP DESIGN -- PARAMETERS TO BE MEASURED

The basic concept for the downhole, instrumented pump is a tubing pump inside an instrumentation chamber (see Figure **1).** The instrumentation goes into the annular space between the pump barrel and an outer tube. To provide adequate space for instrumentation without having an excessively large outer tube, the pump barrel is placed off-center within the tube. The pump is a **1.25**" thick-walled brass barrel pump capable of pumping from 8,000 ft. Initially the pump will be fitted with a 6-ft plunger with 6 thousandths clearance between the plunger and barrel. An advantage to the system proposed is that the plunger and valves can be changed without pulling the instrumentation. The instrumentation housing is 3.75" OD with 4.5" OD end fittings which should allow deployment in ***5.5"*** casing. A cable will be strapped to the outside of the tubing to bring data back to the surface. The use of a cable to up-load data in real-time (rather than recording data in memory) allows the surface pumping unit to be adjusted in response to what is measured downhole.

Instrumentation within the annular space must measure through the pump barrel to detect what is going on within the pump -- not an easy task. Thus, compromises must be made in deciding what to place in this space. Measuring when the valves open and close **is** important, but is very difficult especially for the traveling valve since the valve cage moves. Another thing that would be desirable to measure is the gas volume; again that would be very difficult within the space limitations downhole. The concept proposed was to measure the position of the plunger and four pressures: pump discharge, compression chamber, pump intake, and annulus or gas separator intake. Valve action and pump fillage will then be deduced from these measurements. Measurement of the pump position through the pump barrel is a challenge that has been addressed by placing 128 Hall effect sensors on the outside of the pump to form a 7 bit digital representation of the plunger. Figure ***2*** shows 7-bit digitization gives reasonable representation of the plunger position even for one of the more non-sinusoidal plunger motions found in the Downhole Dynamometer Database (Waggoner and Mansure)

DETERMINING VALVE ACTION

The fist task that had to be done with the clear, instrumented pump at University of Texas at Austin was to determine if the measurement of the four pressures and position would be adequate. Figure 3 shows typical pressure and position data as well as load (load will be measured on the surface during downhole instrumented pump tests). Analysis of the data as well as video capture of the standing and traveling valve motion show that it is possible to precisely identify when the valves open and close by measuring when the compression chamber pressure rises above the discharge pressure or falls below the intake pressure. Note: to do this accurately the measured pressures shown on Figure 3 must be corrected for differences in head since the transducers are located at different elevations **(–1.1** psi for the discharge pressure and –-0.4 psi for the intake pressure). While it was clear from the very first data sets collected in Austin that valve action could be determined by measuring pressures, a number of the details of Figure 3 require explanation. Note; other requirements, differentiating between a pumped-off and gas locked well and determining pump fillage, will be discussed later.

The wiggles in the compression chamber and discharge pressures data at the beginning of the downstroke are related to opening and chatter of the traveling valve and are readily understood by examining the video and considering the fluid dynamics of the valve. What was most surprising in Figure 3 is the small-scale variations/oscillations in the load data. Since load is not one of the parameters to be measured by the downhole instrumented pump and since these load fluctuations are the subject of other work at the University of Texas, they will not be discussed in detail here. However, a couple of points are worth noting: **1)** they are real system behavior, not noise and **2)** they **are** quite like behavior that is insignificant in deep wells where the load is much higher. They are real as shown by the corresponding dynagraph of the data (Figure **4).** Five cycles of data are superimposed showing the wiggles in the load repeat and are thus real, not noise in the measurements. The repeatability of the dynagraph data is significant. It demonstrates that once a stable pumping condition has been reached, only one cycle of data is needed to analyze performance of a pump. Conversely, if variations are seen in the measurements, it is most likely due to changes in well conditions such as drawdown or gas to oil ratio rather than chaotic behavior of the pump.

COMPRESSION CHAMBER PRESSURE

At the end of the downstroke when the traveling valve closes and the plunger starts up, the pressure (P_x^U) in the compression chamber (the space in the barrel in-between the standing valve and traveling valves) will be approximately the pump discharge pressure (P_d) During the time when both valves are closed, the pressure within the compression chamber drops as a result of the upward motion of the plunger expanding the compression chamber volume creating "suction." If there is no gas in-between the valves and the fluid compressibility and slippage is low, then the change in compression chamber pressure is essentially instantaneous. When gas is trapped between the valves, the pressure, assuming dead oil (oil for which no gas breaks out as the pressure drops), can be approximated as a function of plunger position (X) by gas laws (see Figure 5):

$$P_x^U \cong P_d\left(L_{g0}/(L_{g0}+X)\right)^{\gamma} \quad (1)$$

where L_{g0} is the effective length or volume/area of gas between valves at beginning of upstroke.

For isothermal expansion/compression, $\gamma=1$ For adiabatic expansion/ compression $\gamma=Cp/Cv$.
For air at atmospheric pressure, $\gamma=$ **1.37** (for the laboratory tests reported in this paper, the gas used was air).

Figure 5 shows data when the pump **is** "full," but has geometrically trapped gas - gas in the annulus between the barrel and traveling valve that is not expelled on the down stroke (see Figure 6). **A** "full pump" means only liquid flows into the pump. The effective length of the gas trapping space was measured to be 0.6 in. The figure shows that for a full pump, the pressure rises and falls rapidly (in **~0.3** sec.) and the difference between isothermal and adiabatic expansion/ compression is insignificant. For a full pump, the pressure rises and falls rapidly enough that only **2%** of the stroke is wasted between the bottom of the downstroke and the point where the standing valve opens. In the field, where stroke lengths are typically much longer than in the lab, the percentage will be even less.

Figure **7** shows gas expansion and compression when the well is "pumped-off' - no liquid flows into the pump. Note: when comparing Figures 5 **& 7,** there is a change of time scale; the full pump example is at 5.8 **SPM** while the pumped-off example is at **17.5 SPM.** Since the pump has adequate "compression" to expand and contract the gas, on Figure 7 both valves open and gas is produced through the pump even though no fluid moves through the pump, that is the pump is not gas locked, it is producing gas only. This has been confirmed visually. Figure 7 shows that for this pumped-off example compression during the downstroke takes a longer time, 0.85 sec., or 50% of the stroke.

Note from Figure **7** that the effective gas trapped has increased from the measured space to ~2.0." Apparently, for the full pump example, the pump history had minimized the trapped gas, where as, for the "pumped-off' condition, additional gas was trapped because of incomplete separation during the downstroke (bubbles were observed). For the pumped-off example, 8% of the upstroke is wasted between the bottom of the downstroke and when the standing valve opens. Again in the field, where stroke lengths are typically much longer than in the lab, the percentage will be even less.

Figure 8 shows an expanded view of the gas compression during the downstroke. In this case, the difference between isothermal and adiabatic compression is very significant and the measured data falls in-between these two conditions. Thus, for a pumped-off well it possible to distinguish isothermal vs. adiabatic compression.

For short times (full pump), there is not enough time for energy to flow from the barrel to the gas inside the barrel and thus one would expect the process to be adiabatic. For longer times, heat can transfer between the barrel and the gas. For 0.8 sec., it is estimated that heat transfer will cancel as much as **30%** of the adiabatic temperature change. Figure 8 shows that if γ is reduced to **1.26 (70%),** the predicted pressure rise matches the measured data reasonably well.

GAS LOCKING

If during the beginning of the upstroke expansion fails to drop the pressure of gas in the compression chamber pressure below the pump intake pressure (P_i) the standing valve will not open and the pump becomes gas locked. According to equation 1, the pump will gas lock if

$$P_{X-S}^{U} = P_d\left(L_{g0}/(L_{g0}+S)\right)^r > P_i \text{ or } \frac{P_d}{P_i} > \left(1+\frac{S}{L_{g0}}\right)^r$$

(2)

where **S** is the stroke length.

The compression chamber downstroke pressure is given by

$$P_x^D = \frac{P_i\left[(1-f)S + L_{g0}\right]^r}{\left[X + L_{g0} - fS\right]^r} \quad (3)$$

where f is the pump fillage. It can be shown that as the fillage goes to zero, this equation gives the same gas locking condition as equation *2.*

From equation 1 and the corresponding equation for gas compression on the downstroke, it is possible to calculate compression chamber pressure for a gas locked well (Figure 9). Note the symmetric shape of the compression chamber for a gas locked well in contrast to the pumped off well Figure 7; where as, for a pumped-off well there are high and low pressure plateaus when the valves are open. Thus, the measurements proposed for the downhole instrumented pump will allow the differentiation of a "pumped off" well and a gas locked well. The contribution to the load due to compression chamber changes is calculated from $(P_d\text{-}P_x)A$ where **A** is the area of the plunger. This is shown as a dynagraph in Figure 9

DETERMINING PUMP FILLAGE

The primary measurements that will be made with the downhole instrumented pump will be position and compression chamber pressure. Like a downhole card that cross plots load and position, pressure and position can be cross-plotted (see Figure 10). One could learn how to interpret the patterns of Figure 10; However, it is more instructive to plot $(\text{Pressure})^{-1/r}$ vs. position (see Figure 11). Figure 11 can be understood by rewriting equation 1 & 3 as

$$\left(1/P_x^U\right)^{1/r} = \left(1/P_d\right)^{1/r}\left(\frac{1}{L_{g0}}\right)\left(X + L_{g0}\right)$$

$$\left(1/P_x^D\right)^{1/r} = \left(1/P_i\right)^{1/r}\left(\frac{1}{(1-f)S + L_{g0}}\right)\left(X + L_{g0} - fS\right) \quad (4)$$

Thus plotting $(\text{Pressure})^{-1/r}$ vs. position converts the compression and decompression curves on Figure 10 into straight lines while keeping the intake and discharge pressure portions as horizontal lines. Fitting compression and decompression lines to Figure 10 allows the gas trapped between the valves at the beginning of the upstroke and the fillage to be determined from the point where $(\text{Pressure})^{-1/r} = 0$. Note, at this point equations **4** reduce to

$$0 = \left(X + L_{g0}\right)$$

$$0 = \left(X + L_{g0} - fS\right) \quad (5)$$

There are three parameters that have to be adjusted to get a good fit: K, Lgo, and f. Figure 12 is what the plot looks like when these parameters are not adjusted properly. It is relative easy to adjust the parameters until a good fit is obtained or the process could be automated, the analyst picking the compression and decompression intervals and least squares fits used to determine the parameters.

Figure 11 demonstrates a second requirement for a successful downhole instrumented pump can be met with the design proposed: pump fillage can be determined from compression chamber pressure and position.

MODELING INSTRUMENTED PUMP LOAD

Process for determining fillage by comparing measured data to the physical law governing the compression and decompression of gas demonstrates the value of developing a physical model of sucker rod pump behavior. In addition to compression and decompression of gas, other physical phenomena to be modeled include friction, pressure drops across the valves, gas breakout, acceleration, etc.

The simplest of models was used to develop the downhole card for the gas locked well example (see Figure 9). In this case the pressure is given by equation 1 and that is all that is needed to produce the pressure plots, either pressure vs. time or pressure vs. position. Of course position vs. time must be known. That can be from measured data or sinusoidal motion can be assumed: $S(1-\cos(2\pi\ SPM\ t/60)/2$. Analyses of laboratory data showed position deviated from sinusoidal motion by 10% without causing significant errors in assuming sinusoidal motion. Whether deviations from sinusoidal motion are significant for field data like Figure 2 has not been determined. To model load not just pressure, load is calculated from $(P_d-P_x)A$. The load calculated this way is the effective buckling load; if the true load at the pump is desired, P_d must be multiplied by the area of the rods rather than the area of the plunger. To calculate the surface load, the weight of the rods in fluid is added to the buckling load.

As the modeling gets more complex, it is necessary to break the function of the pump down into steps. For example:

If (upstroke) use equation 1
  Until pressure calculated from equation 1 rises above the discharge pressure
  Then switch to the discharge pressure

If (downstroke) use equation 3
  Until pressure calculated from equation 3 falls below the intake pressure
  Then switch to the intake pressure.

Similar schemes are being developed to account for the direction the frictional forces and the change from static to dynamic friction as well as other processes. Figure 12 shows the display of the model being developed to analyze the instrumented pump data.

CONCLUSIONS

The laboratory instrumented pump installed at the University of Texas at Austin has demonstrated that the design chosen for the downhole instrumented pump will meet the objectives of the project: it will allow determination of when the valves open and close, of gas locked wells, and of pump fillage. Analysis of the data collected has shown the value of collecting high-speed information. High-speed data for the shallow depth of the laboratory well shows vibrations that become insignificant in deep wells, but this can be distinguished from significant high-speed phenomena such as occurs when the valves open. Modeling has been proven valuable in understanding the laboratory data. Modeling of pump barrel pressure has progressed to the point that it can be used in the field to interpret downhole instrumented pump data

NOMENCLATURE

A = *Area of plunger (sq. in).*

c = *Ratio of the clearance between the valves to the stroke (dimensionless).*

f = *Pump fillage of swept volume (dimensionless). Gas between standing and traveling valve must be added to get " total pump fillage."*

L_g = *Effective length (in) of gas between valves.*

L_{g0} = *Effective length (in) of gas between valves at beginning of upstroke.*

m = *Gas to fluid volumetric ratio (dimensionless).*

P_d = *Pump discharge pressure (psia) approximately hydrostatic head pressure (psia) in tubing.*

P_i = *Pump intake pressure (psia).*

P_x^U = *Compression chamber upstroke pressure (psia) when plunger is at X.*

S = *Stroke (in) of pump.*

SPM = *Strokes per minute (per minute). t=Time (seconds).*

X = *Position (in) of plunger relative to beginning of upstroke.*

9 = *Heat capacity ratio (dimensionless):* C_p/C_v

REFERENCES

Waggoner, J. R. and Mansure, **A. J.**, "Development of the Downhole Dynamometer Database" SPE 37500 presented at the SPE Production Operations Symposium, Oklahoma City OK, March 9-11, 1997

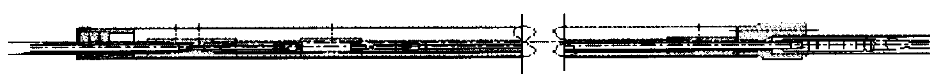

Figure 1 - Downhole Pump Instrumentation Chamber.

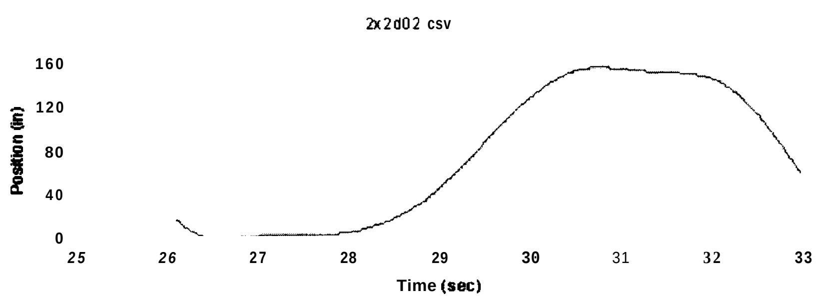

Figure 2 - 7 Bit Digitization of Plunger Position

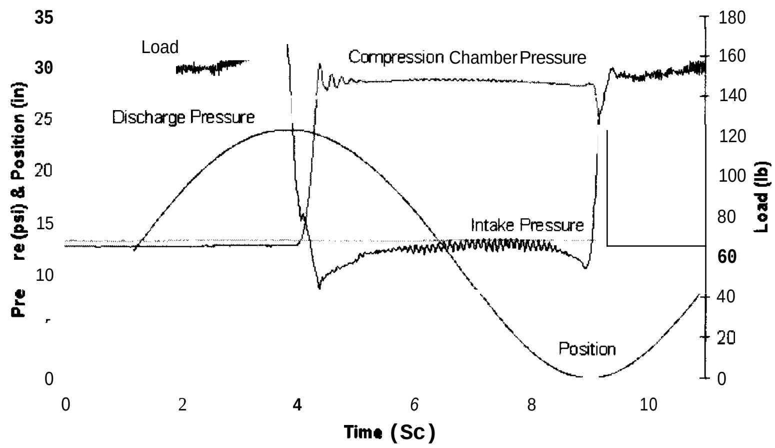

Figure 3 - Typical Pressure and Position Data

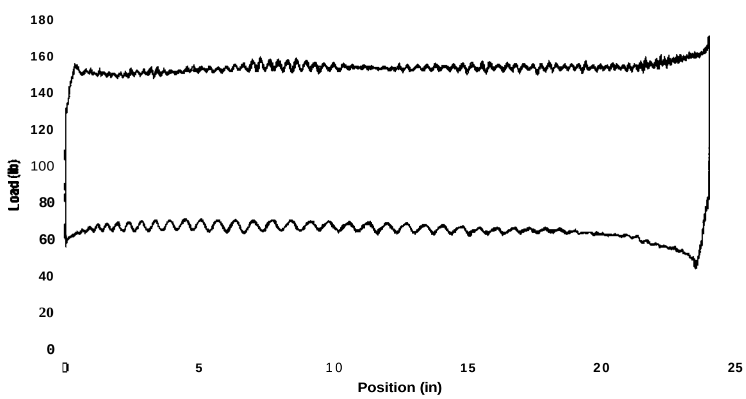

Figure 4 - Five Cycles of **Superimposed Dynagraph Data Typical** of **Measurements at Austin**

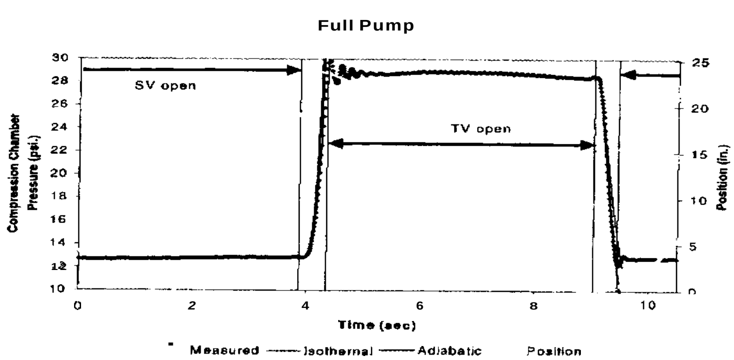

Figure 5 - isothermal vs. Adiabatic Compression for Full Pump

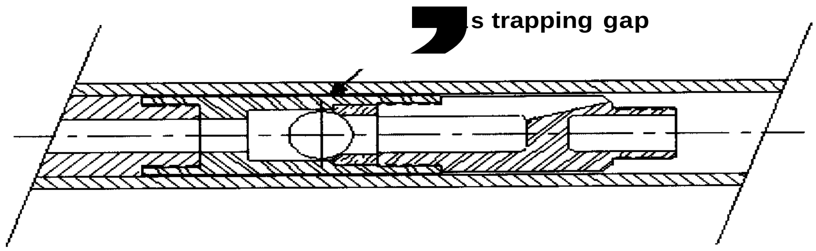

Figure 6 - Space Around Traveling Valve that Traps Gas (L_{go}~0.6")

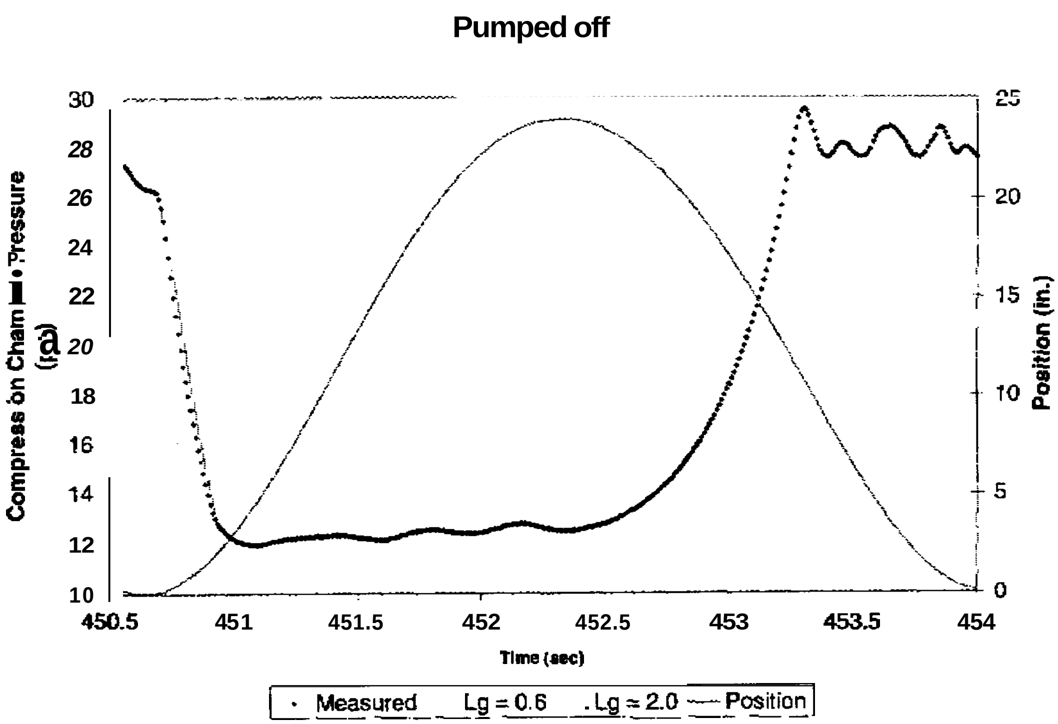

Figure 7 - Compression Chamber Pressure for Pumped-Off Well

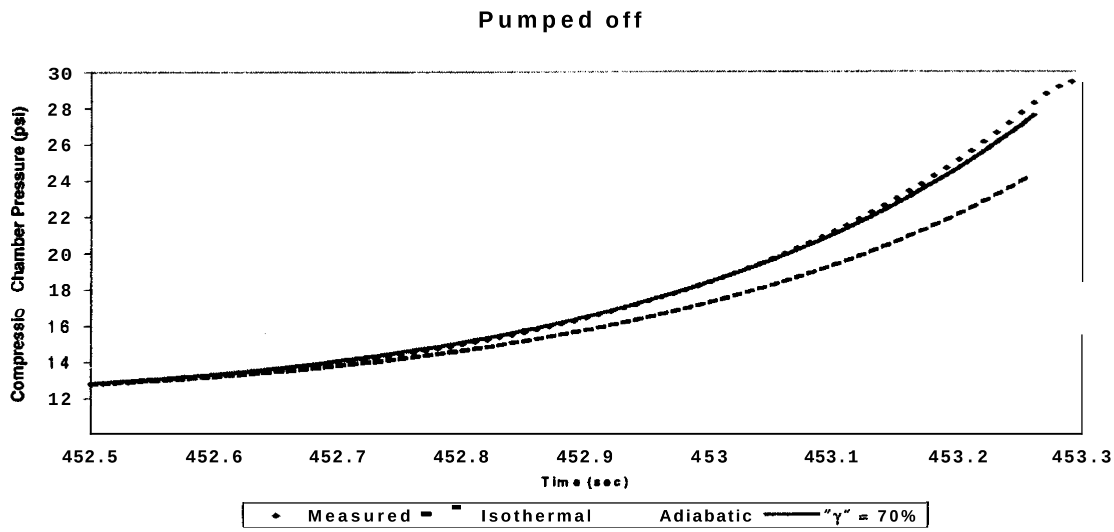

Figure 8 - Expand View of Isothermal vs. Adiabatic Compression on Downstroke

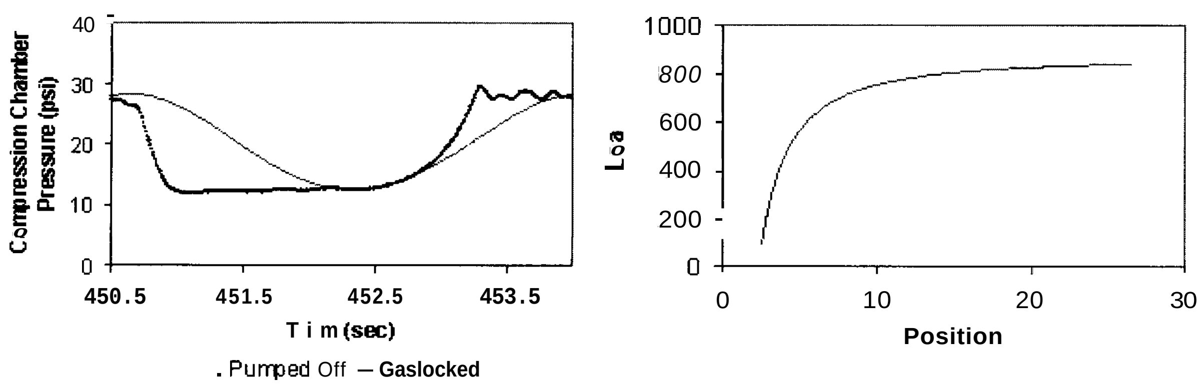

Figure 9 - Gas Locked Compression Chamber Pressure and Dynagraph