PLUNGER LIFT OPTIMIZATION BY MONITORING AND ANALYZING WELLBORE ACOUSTIC SIGNALS AND TUBING AND CASING PRESSURES

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ABSTRACT

Plunger Lift operations are oftentimes not optimized due to lack of knowledge of plunger location and changes in tubing pressures, casing pressures and bottomhole pressures. Monitoring the plunger location in the tubing helps the operator (or controller) to optimize the production of liquid and gas from the well. In low liquid volume wells, the plunger position can be tracked from the surface by monitoring acoustic signals generated as the plunger falls down the tubing. When the plunger falls through a tubing collar recess, an acoustic pulse is generated. These acoustic pulses, generated at the tubing collar recesses, travel through the gas in the tubing and can be monitored at the surface to obtain plunger depth. These acoustic pulses are converted to an electrical signal by use of a microphone or pressure transducer. The signal is digitized, and the digitized data is stored and processed in a computer to determine plunger depth. In some high liquid volume wells, the acoustic pulses generated as the plunger falls past the tubing collar recesses may be masked and not detectable due to liquid accumulation around the plunger. However, in both low and high liquid volume wells, the plunger depth can be determined by generating an acoustic pulse in the tubing at the surface, and then, by monitoring the acoustic reflection from the top of the plunger. Multiple shots are taken, so the plunger descent rate can be determined throughout the plunger fall. Software processes this plunger depth data along with the tubing and casing pressure data to display plunger depth, plunger velocity and well pressures vs. time. Plunger arrival at the liquid level in the tubing, and plunger arrival at the bottom of the tubing are identified on the data plots. Well inflow performance is calculated and plotted. Software displays the data and analysis in several formats including a pictorial representation of the well showing the tubing and casing pressures, plunger location, gas and liquid flow rates in the tubing and annulus, and also, inflow performance relationship at operator selected intervals throughout the cycle. A field case is presented to show how this field data analysis is applied to optimization of Plunger Lift operations.

INTRODUCTION

Plunger lift has become more popular in recent years due to better mechanical equipment, improved electronic controllers and a better understanding of the operating system[1-13]. A portable plunger lift data acquisition and analysis system has not been available so that the performance of the plunger lift system can be fully analyzed and understood. This paper describes a new portable data acquisition system that allows the operator to analyze a plunger lift system, and then, improve the well's production by optimizing the shut-in and flow times and other operational parameters that are associated with the plunger lift system.

A feature of the plunger lift artificial lift system is that the reservoir gas energy is used to lift the liquids to the surface without addition of external power. Thus, plunger lift systems are less expensive to operate and install than most other artificial lift systems. However, a limitation of plunger lift is that sufficient energy in the form of compressed gas from the reservoir must be available in the wellbore to lift the produced liquid to the surface. Also, the producing bottomhole pressure must be sufficient to lift the produced liquids from the reservoir to the surface and also overcome surface pressure.

Please refer to Figure 1 for a schematic of a typical plunger lift system. The plunger lift operation is separated into **3** stages, namely, the Unloading, the Afterflow and the Shut-in. In this paper, data is analyzed during a complete cycle, which includes the Unloading, Afterflow and Shut-in periods. The beginning of the analysis cycle is the beginning of the Unloading period, and the analysis continues through the end of the Shut-in period. Following is a discussion of a normally operating plunger lift system.

Unloading begins when the surface flow line valve opens, and production from the well commences. When the surface valve is opened, a drop in pressure causes the gas in the tubing to flow into the flow line and surface facilities. The pressure below the plunger pushes the plunger (along with the accumulated liquid above the plunger) up the tubing.

The gas that is stored in the casing annulus along with gas that is produced from the formation expands and provides the energy required to lift the plunger and liquid slug. As the plunger approaches the surface, the liquid slug that exists above the plunger is produced into the flow line and surface facilities. After all of the liquid above the plunger is produced into the flow line, the plunger arrives at the surface and is held at the surface by gas flowing up the tubing behind the plunger. The plunger acts as a solid interface between the liquid slug above the plunger and the expanding gas below the plunger. The plunger reduces gas breaking through the liquid slug and decreases liquid fallback. Since the pressure below the plunger, when the plunger is rising, is greater than the pressure above the plunger, very little liquid leaks from above the plunger to behind the plunger as the plunger travels upward. The main leakage past the plunger is gas from below the plunger slipping upward past the plunger.

Afterflow occurs when gas is produced from the well after the plunger has reached the surface (normally in high gas-liquid ratio wells). If all of the gas that is produced from the reservoir contains more energy than is required to lift the liquids to the surface, some gas can be produced after the plunger has arrived at the surface to increase gas production. In most cases, during the afterflow, liquid is not produced at the surface. Sometimes, the gas flow rate up the tubing is sufficient to lift liquid to the surface; but in most cases, the liquid accumulates at the bottom of the tubing as an aerated liquid column while gas flows through the aerated liquid to the surface. This accumulation of liquid at the bottom of the tubing increases the backpressure against the reservoir and restricts both gas and liquid production from the well. The Afterflow period is long in a well that produces a lot of gas with a limited amount of liquid and is short in a well that produces a limited amount of gas with a lot of liquid.

The Shut-in period starts when the flow line valve is closed at the end of the afterflow period. When the flow line valve is closed, the plunger begins its fall to the bottom of the tubing. During this Shut-in period, gas and liquid flow from the well is stopped, and the gas produced by the reservoir is primarily stored in the casing annulus. Normally, a liquid slug collects in the bottom of the tubing. Some gas will also collect in the tubing above the liquid. It is important to understand that gas and liquid continue to be produced from the reservoir during all of the Unloading, Afterflow and Shut-in periods.

SURFACE MEASUREMENTS AND FLUID FLOW

Surface pressures are monitored continuously on the casing and tubing so that well performance can be determined. The casing pressure measurements allow calculation of the gas volumes and gas flow rates into an out of the casing annulus. The tubing pressure measurements along with the casing pressure measurements allow calculation of the gas volumes and flow rates in the tubing as well as the volume of liquid present in the tubing. The combined gas and liquid flow rates allow an analysis of the well's inflow performance. The performance of the plunger lift system can be described by combining the casing annulus and tubing fluid volumes and flow rates with the reservoir flow properties and plunger location during the plunger lift cycle.

During unloading, the surface flow valve is opened, and the pressure on top of the liquid and plunger decreases because tubing gas flows into the low-pressure flow line. If the pressure below the plunger exceeds the pressure at the surface plus the pressure due to the gas column plus the pressure due to the liquid column above the plunger plus the pressure due to the weight and area of the plunger plus plunger friction, the plunger and liquid above the plunger move upward. A drop in pressure at the surface is generally observed during the unloading cycle as the liquid slug is rising. When the liquid reaches the surface, flow restrictions that are normally present in the surface piping and surface facilities cause the pressure at the top of the tubing to increase as the liquid is forced down the flow line. Although the height of the liquid above the plunger becomes less so that the plunger with associated liquid is easer to lift, the flow path at the surface has restrictions to liquid flow that may increase the pressure at the surface substantially. When sufficient pressure exists below the plunger, the plunger will be pushed to the surface with the liquid slug being displaced down the flow line. As the plunger is forced upward by the pressure below the plunger, the formation is producing both gas and liquid. This liquid accumulates in the bottom of the tubing and reduces the gas pressure that is lifting the plunger. The average gas flow rate at the surface during unloading can be determined by calculating the volume of gas in the tubing above the liquid and dividing by the time required for the liquid to travel to the surface.

During the afterflow period, the casing pressure decreases as gas flows from the casing annulus into the tubing. In addition, the gas and liquid production from the formation flows into the tubing. The formation gas and liquid flow rates are determined from a calculated producing bottomhole pressure and the inflow performance relationship data that is obtained during the Shut-in period. Thus, the volume of gas that flows from the casing annulus into the tubing and the volumes of gas and liquid that flows from the formation into the tubing can be calculated. The liquid from the formation normally collects in the bottom of the tubing because the gas flow rate up the tubing is not sufficient to lift the liquids to the surface.

During the shut-in period, gas and liquids produced from the reservoir are stored in the casing annulus and tubing. In most conditions, the majority of the gas is stored in the casing annulus and the majority of the liquid is stored in the tubing. Some gas will be stored in the tubing above the liquid, and the volume can be calculated using surface pressure measurements. In most cases, all of the liquid above the tubing intake accumulates inside the tubing due to the excess compressed gas in the casing annulus that flows into the tubing and forces any liquid in the casing annulus above the tubing intake into the tubing also.

The gas volumes in the casing and tubing are calculated from wellbore dimensions, surface pressures, and gas properties. The gas gravity is calculated from the acoustic velocity obtained from an acoustic liquid level test. The flow rates are the first derivative with respect to time of the flow volumes. The formation gas flow rates can be accurately calculated at any time during the shut-in period. Also, the producing bottomhole pressures are calculated throughout the shut-in period[14-16]. Thus, a major portion of the well's inflow performance relationship is known from actual well measurements during the Shut-in period. The well's inflow performance during Unloading and Afterflow is assumed to be the same as the well's inflow performance during Shut-in. This is not exactly correct due to formation storage", but this assumption is used for determining formation flow rates during the Unloading and Afterflow periods.

The bottomhole pressures are calculated at the operator entered formation depth. Each operator will have a different thought about the proper depth to use. The bottom, the top, and the middle of the formation are all reasonable choices depending upon the particular well. In a gas well, the formation gas-liquid contact depth is a reasonable choice. In an oil well, the bottom of the formation might be used. The bottomhole pressures are calculated at the tubing intake, and then adjusted to the formation depth.

LIQUID ACCUMULATION

The difference in tubing and casing pressures at the end of the shut-in period indicates the difference in height of a gas-free liquid column in the tubing and in the casing annulus. The casing and tubing pressures and buildup rates are analyzed to verify that all of the liquid did accumulate in the tubing. When the height of the liquid column in the tubing is known, the volume can be calculated. This is the procedure used in this analysis to calculate the volume of liquid in the tubing at the end of the Shut-in period. The liquid flow rate from the formation is assumed to be proportional to the gas flow rate from the formation. An assumption is made that the liquid in the tubing accumulates proportional to the gas flow rate from the formation into the wellbore during the Unloading, Afterflow and Shut-in cycles. The minimum accumulated liquid at the very bottom of the tubing occurs when the plunger (and liquid slug) begins its upward travel, and the maximum accumulated liquid at the bottom of the tubing occurs at the end of the Shut-in period when the plunger is resting on bottom.

During the Shut-in period, another technique to determine the amount of liquid in the tubing is to perform acoustic liquid level surveys down the tubing. At the very beginning of the Shut-in period, the acoustic pulse will be reflected off the plunger so that the distance to the plunger will be monitored as it falls. After the plunger enters the liquid, the acoustic reflection will be from the top of the liquid. When an acoustic shot is performed down the tubing, acoustic reflections are obtained from the tubing collar recesses and the number of tubing collar recesses to the plunger or liquid level can be used to determine depth. Or, the round-trip travel time of an acoustic pulse generated at the surface combined with the gas acoustic velocity allows calculation of the plunger depth. In this paper, the determination of plunger depth is based on the round-trip travel time of an acoustic pulse generated at the surface (measured with the tubing pressure transducer) and gas acoustic velocity properties obtained from an initial acoustic test down the casing annulus. The distance to the top of the gaseous liquid column in the tubing is calculated using the same procedure.

If measurement of liquid accumulation in the casing annulus is desired, an acoustic liquid level test can be performed down the casing annulus. However, if the liquid level is below a perforated or open-hole interval, the exact depth of the liquid level may be difficult to determine due to multiple acoustic reflections from anomalies other than the liquid level. An analysis of the casing pressure and tubing pressure buildup rates also indicates whether liquid is present in the casing annulus.

Normally, the bottom of the tubing is positioned between the mid-portion of the formation and slightly above the formation. In occasional situations, excess gas from below the bottom of the open-ended tubing bubbles upwards and enters the open-ended tubing. The excess gas will accumulate in the tubing, and the pressure caused by the excess gas will force the liquid out of the bottom of the tubing and into the casing annulus. In this situation, where liquid accumulates in the casing annulus instead of the tubing, liquid will not be collected above the plunger when the plunger falls to the bottom of the tubing during the Shut-in period. When the plunger is brought to surface, the liquid that is in the casing annulus will be pushed into the tubing below the plunger and will collect at the bottom of the tubing unless the gas flow rate is sufficient to lift the liquid to the surface. Most often, the gas flow rate in the tubing is not sufficient to lift liquid to the surface unless the liquid is contained above the plunger. This condition will result in complete failure of a plunger lift system. Plotting and comparing the casing annulus and tubing pressures and buildup rates during shut-in can detect this condition. The casing pressure buildup rate should exceed the tubing pressure buildup rate near the end of the Shut-in period to verify that most of the gas is entering the casing annulus and that the liquid is entering the tubing. The bottom of the tubing should be configured to prevent upward vertical gas flow into the tubing during the shut-in period. In general, the tubing should not be run open-ended, or even worse, with a collar on the bottom of the tubing. The bottom of the tubing should be closed to upward vertical gas flow by installing a collar and a bull plug at the bottom of the tubing. The bull plug should be perforated on the side with 6 or 8 large holes. This problem will be less prevalent if the tubing intake is placed near the bottom instead of near the top or above the formation.

PLUNGER TRACKING

In this analysis, the fall of the plunger is monitored from the beginning to the end of the shut-in period by obtaining acoustic liquid level tests down the tubing at one minute intervals during the plunger fall. An acoustic Gas Gun is used to generate the acoustic pulse. The round-trip travel time is measured for each test. The round-trip travel time is divided by two to obtain the one-way travel time. The one-way travel time is multiplied by the acoustic velocity to determine the depth to the plunger or the liquid level (when the plunger has fallen below the liquid level). The acoustic velocity and gas properties are determined at the beginning of the plunger lift analysis by conducting an acoustic test down the casing annulus. The acoustic velocity is adjusted for variations due to pressure changes. The acoustic liquid level test will not monitor the plunger location when the plunger is submerged in the liquid.

A conventional Gas Gun with a pressure pulse generator and a sensitive twin-disc noise canceling acoustic microphone is attached to the tubing at the surface. The acoustic microphone is also used to sense liquid flow at the surface. Acoustic noise is generated when liquid flows at the surface, and a high noise level indicates liquid flow in the vicinity of the microphone. The microphone and also the tubing pressure sensor can detect the arrival of the liquid and the plunger. Please refer to the graphs.The Gas Gun microphone is also used to detect plunger location during plunger fall. A phenomenon that has been observed is that an acoustic pulse is generated when the plunger falls past a tubing collar recess. The tubing collar recess has an area of approximately 2 sq. in. in 2 in. tubing and 3 sq. in. in 2-7/8 in. tubing. A difference in pressure exists across the plunger as it falls depending upon the weight and area of the plunger and other factors. This difference in pressure might be from 2 to 10 PSI. Thus, as the plunger falls past the recess, an acoustic pulse is generated from the rapid release of the higher-pressure gas in the recess volume to the tubing above the plunger. This acoustic pulse, which is generated at the tubing collar recess, travels through the gas to the surface and is detected by a microphone and also the tubing pressure transducer. These acoustic pulses are normally obtained when a plunger falls down the tubing in a well that produces a limited amount of liquid so that the tubing interior is relatively dry. These tubing recess pulses are monitored at the surface so that the plunger travel is followed on a continuous basis. When the plunger enters the liquid, these acoustic pulses are not transmitted through the liquid, so the noise level drops. This drop in noise level indicates that the plunger is submerged in the liquid. The plunger location cannot be monitored by this technique when the plunger is submerged in the liquid.

Another phenomenon that has been observed is that when the plunger hits the liquid, the tubing pressure increases and the acoustic noise decreases. Additional testing is being conducted to study this observation. Also, the plunger arrival at bottom has been detected in the tubing pressure and the acoustic traces in most cases. Previously analyzed data indicates that the plunger falls about 150 feet per minute when submerged in liquid, and this rate is used in the software analysis.

PREDICTIVE SOFTWARE MODELS

Software models[2] are used to predict the performance of plunger lift systems as a function of well depth, casing and tubing sizes, fluid properties, reservoir pressure and inflow performance, gas and liquid flow rates and other variables. The accuracy of the model can be verified and improved using the results of the measured plunger lift performance data as acquired in this paper. A model should be useful for optimizing flow and shut-in times.

EQUIPMENT REQUIREMENT FOR PLUNGER LIFT ANALYSIS

The equipment required for a standard test is a computer, software, analog to digital converter[16], casing pressure sensor, tubing pressure sensor and an acoustic gas gun. The pressure and acoustic data is acquired at 30 samples per second throughout the test. This data rate is necessary to obtain the desired plunger depth accuracy. The data is acquired for at least one complete cycle of Unloading, Afterflow and Shut-in periods. **Also,** during Shut-in, an acoustic pulse is generated in the tubing, once each minute, so that the location of the plunger during plunger fall and the liquid level depth at the end of the shut-in period can be determined.

ANALYSIS

The previous discussion indicates that the following plots as a function of time can be obtained from the measured surface data.

- Casing annulus gas volumes
- Casing annulus gas flow rates
- Tubing gas volumes
- Tubing inlet and outlet gas flow rates
- Amount of liquid in the bottom of the tubing
- Producing bottomhole pressures
- Formation gas and liquid flow rates
- Tubing gas flow velocities
- Tubing gas flow regime
- Plunger depth
- Plunger velocity

Also, a schematic of the well shows the casing pressures, tubing pressures, gas flow rates, liquid flow rates and plunger location throughout the entire cycle including the Unloading, Afterflow and Shut-in periods. This allows the operator to observe the performance of the well throughout the cycle.

DISCUSSION OF ANALYSIS

Figure 2 shows a graph of casing pressure, tubing pressure and acoustic data acquired over a 2 hour 5 minute period. Initially, the well had been shut-in for three days. Thus, the initial casing pressure and the acoustic survey allow calculation of the SBHP. The test shows two cycles of data. The test should be continued until the well is stabilized for an analysis of the well's performance. The graph shows the change in the well's performance as the well unloads when the liquid is removed from the wellbore. The notations on the graph show the beginning of the Unloading period, the arrival of liquid at the surface, the arrival of the plunger at the surface, the Afterflow period, the beginning of the Shut-in period, the arrival of the plunger at the liquid, the arrival of the plunger at the bottom of the tubing, and then the beginning of the next cycle.

Figure **3** is **a** tabulation of the plunger position data, and a plot of the plunger depth and fall rate during the Shut-in period. The depth to the top of the gaseous liquid column in the tubing is also shown.

Figure 4 shows a schematic of the Plunger Lift System throughout the Unloading, Afterflow and Shut-in periods. Actuating the analysis causes the display to show the position of the plunger, the flow rates, the casing and tubing pressures and liquid in the tubing during one complete cycle as a function of time. The display automatically changes once each second and displays the well's performance in one-minute intervals. Thus, an Unloading, Afterflow and Shut-in cycle of 50 minutes duration requires 50 displays to show the complete cycle, and require 50 seconds of time.

SOFTWARE

The Plunger Lift software program is part of the Total Well Management (TWM) software that includes acoustic, dynamometer, motor power and current, and pressure transient data acquisition and analysis. This software program is used with **an** analog to digital converter to acquire data. Formerly acquired data can be analyzed using this program without the use of an analog to digital converter. TWM can be downloaded free at www.echometer.com. Previously acquired plunger lift data can be obtained from info@echometer.com to run in the TWM software to view the analysis performed.

SUMMARY

The casing pressure, tubing pressure and acoustic noise can be monitored in a plunger lift system to determine the performance of the well including the formation flow rates, plunger location, liquid accumulation, and bottomhole pressures. This analysis can be used to optimize Shut-in and Flow times for maximum well production.

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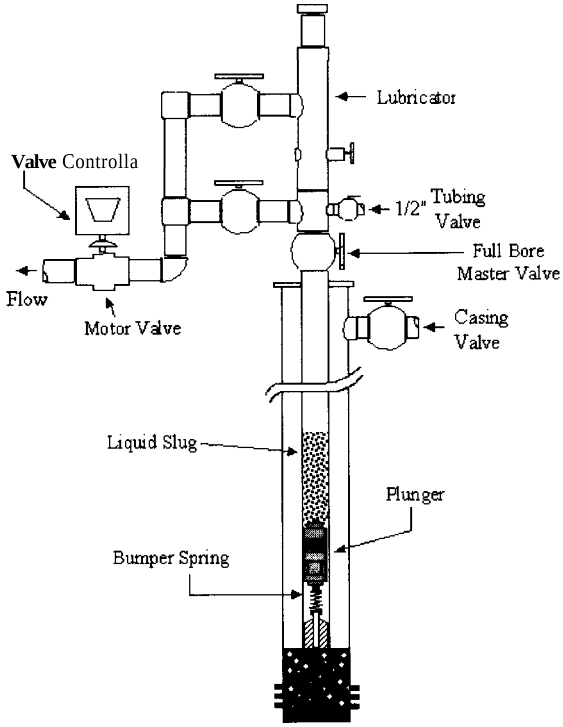

Figure 1 - Plunger Lift System

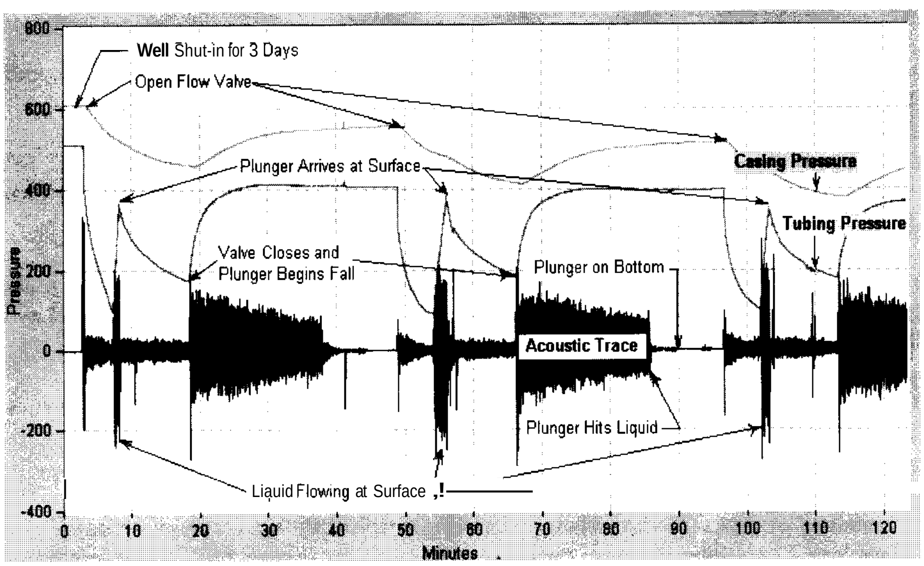

Figure 2 - Casing Pressure and Tubing Pressure and Acoustic Traces

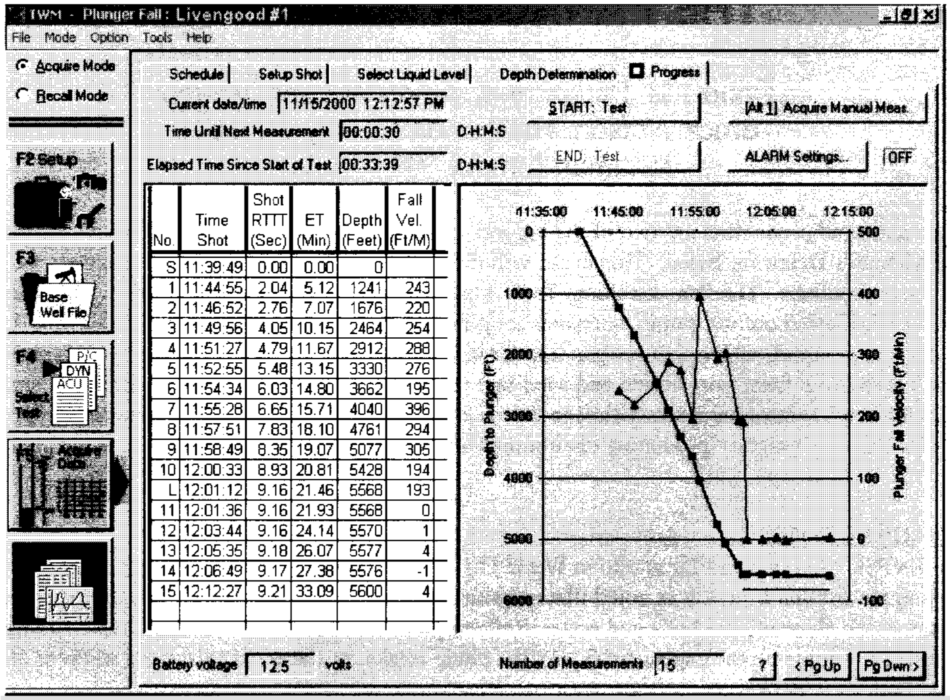

Figure 3 - Plunger Fall Data and Graph

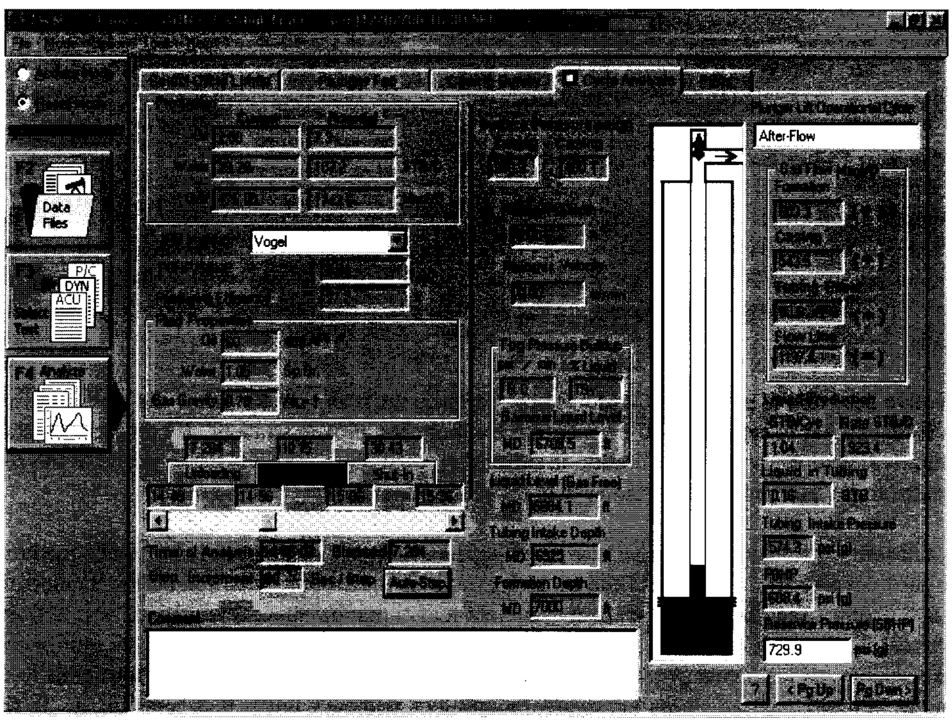

Figure 4 - Plunger Lift Cycle Analysis