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Plunger Lift Analysis, Troubleshooting, and Optimization

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Abstract

A new portable monitoring system has taken the guesswork out of plunger lift analysis, troubleshooting and optimization. The plunger generates an acoustic pulse as it falls through each tubing collar recess when the well is shut-in. Each acoustic pulse travels through the gas in the tubing and is detected at the surface. The pulses are converted to an electrical signal by a microphone and pressure transducer. The signals are digitized, stored and processed in a computer to determine plunger position, plunger fall velocity, and plunger arrival at the liquid level in the tubing. The problem of not knowing the plunger location during the operation cycle has been overcome with this new technology by allowing the operator to see the plunger location at any time during the cycle. Having a detailed analysis of the operation of the well makes optimization of plunger lift production achievable with a minimum of effort and avoids the usual waste of time due to trial and error procedures. Example data collected from various plunger lifted wells are presented in this paper to show how to identify operational problems such as holes in the tubing, stuck plungers and plungers not getting to bottom

Introduction

Plunger lift is a low cost method for lifting liquids (water, condensate and/or oil) from primarily liquid loaded gas wells and is used infrequently to produce oil wells. The operating cost of plunger lift system is low compared to other artificial lift methods, because the reservoir supplies the energy required to lift the liquids. During plunger lift operations the motor controlled valve is opened and at a later time shut-in. During shut-in the gas flow down the flowline is stopped when the surface valve is closed, allowing time to elapse for the plunger

to fall down to the bottom of the tubing. After a pre-determined amount of time elapses the controller commands the motor flow valve to open and the tubing pressure begins to drop toward the flowline pressure. Differential force acting on the plunger results from the drop in surface tubing pressure and the high reservoir pressure below the plunger. The differential force lifts the plunger and a portion of the liquid above the plunger to the surface. The open and shut-in operational cycle of the plunger lift system is repeated throughout the day to produce liquids and gas from the well.

Without acquiring a fluid level shot in plunger lift wells, an acoustic fluid level instrument can be used to continuously record at a fast sampling rate the acoustic signal produced as the plunger travels up and down the tubing and to monitor the variation of pressures during the plunger cycles. The acquired acoustic and pressure data can be processed to determine the 1) depth to the plunger 2) fall velocity of the plunger 3) time for the plunger to fall to the liquid 4) time for the plunger to fall to the bottom of the tubing 5) the volume and rate of gas flowing into the well 6) the appropriate cycle times for optimum operation. As the data is collected and analyzed at the well, the goal for the plunger lift analyst should be to answer the WELL PERFORMANCE QUESTIONS listed in Table 1. The plunger lift well can be produced more efficiently if the well performance questions are answered. Analysis of the collected data is used to optimize and troubleshoot the operation of plunger lifted wells.

The following sections of this paper describe the procedure used to acquire the data for plunger lift analysis. Example data showing various operational problems encountered during operation off plunger lift systems will be presented.

Plunger Lift Operation Cycle

The plunger lift cycle can be divided into three distinct parts[1]:

1-The ***Shut-in*** period begins when the flowline motor valve closes, the flow is shut-in and the plunger falls down the tubing. The plunger falls from the surface through the gas in the tubing until the plunger hits the accumulated liquid at the bottom of the tubing. The plunger then falls through any accumulated liquid at the bottom of the tubing. The shut-in time period should be long enough for the plunger should fall to the bottom of the tubing and rest on a plunger catcher or bumper spring. During shut-in, the casing pressure must build to sufficient pressure to be high enough to lift the accumulated fluids and the plunger to the surface during the next time period when the valve opens.

2-The ***Unloading*** period begins after a predetermined amount of time has elapsed from the start of the shut-in period. Based on meeting some type required of operational criteria a valve controller opens the motor valve between the tubing and the flowline. The pressure from the reservoir and the pressure from the gas stored in the casing annulus are used to lift the accumulated liquid and plunger to the surface. During the unloading period the surface tubing pressure drops to a value close to the line pressure and the differential pressure across the plunger lifts the plunger and the liquid slug above the plunger to the surface.

3-The ***Afterflow*** period begins when the plunger arrives at the surface. The flow valves are open as the well produces gas up the tubing and down the flow line. The plunger is held at surface by either the differential pressure caused by the flow of gas past the plunger or a mechanical plunger catcher. Sometimes additional liquid will also be produced with the gas, if the gas velocity in the tubing is high enough to lift liquid to the surface. As the gas rate decreases, liquids are not carried to surface because the gas velocity becomes too low[2] and the liquid will accumulate at the bottom of the tubing. If the afterflow period is too long, the liquid accumulation at the bottom of the tubing will cause the pressure at the bottom of the well to build-up and further reduce the flow from the formation. The after-flow time period should be long enough to bring liquid into the tubing, but not to long that longer shut-in time period is required to bring the plunger and liquid to the surface. After meeting specific control criteria or a predetermined time elapse, the motor valve is closed, starting the next plunger cycle.

The new portable monitoring system can be used to begin acquisition of data at any time during the cycle. At least ONE COMPLETE CYCLE must be acquired to be able to do a complete analysis of the plunger lift system. One complete cycle consists of one valve opening plus one valve closing or one valve closing plus one valve opening. If the operator is only interested in determining the plunger fall velocity, then data acquisition must start just before the Shut-in period begins and continue until after the beginning of the Unloading period. Acquisition of data over several cycles may be required to analyze a well that behaves erratically; in order to identify the problem and to correctly analyze the operation of the plunger lift installation.

Setup of Acquisition Hardware

Over a long time period the electrical signals can be digitized and stored by software in a computer. The acoustic and pressure signals signal are recorded with special software at the optimum resolution of the analog to digital converters. The computer offers unattended operation of the equipment in that the computer can be programmed to acquire data without monitoring by an operator. As the data is acquired the processing speed of the laptop computer allows instant analysis.

The acoustic, tubing and casing signals are acquired at a default sampling rate of 30 measurements per second and data is displayed in real-time sample-by-sample basis. For high-pressure wells or fast falling plungers, faster sampling rates of 60 or 120 samples per second may be needed to follow bumper springs and by-pass types of plungers.

The most common data acquisition hardware for plunger lift includes an acoustic gas gun with microphone and pressure transducer connected to the tubing through a ½" or larger, fully opening valve, connected on the lubricator and a second pressure transducer connected to the casing. It should be noted that if a needle valve is present on the well at the point of gun connection, it should be replaced in order to record the best quality acoustic signal. A full opening ball valve should be used to connect the gas gun to the lubricator. The gas gun should be cocked manually or by charging the gas chamber to a pressure greater than the maximum expected tubing head pressure so that during the unloading and afterflow cycles the well fluids will not enter the volume chamber and contaminate the gun mechanism. Other types of gas guns may require the gas gun chamber to be charged to a pressure greater than the maximum expected well pressure in order to keep the internal gun mechanisms closed. If high well head pressures are encountered when liquid is being unloaded at the surface and the gas gun valve opens, then the internal mechanism of the gun may be contaminated from well fluids and cleaning of the gun may be required upon completion of the test.

The gun's microphone is connected to the portable monitoring system via a coaxial cable and the microphone is used to monitor the acoustic noise throughout the cycle. The

plunger generates noise during the shut-in time period and during the rest of the cycle noise is generated by flowing gas and flowing liquid.

Identifying Key Events During Data Acquisition

The elapsed time for a plunger lift cycle is often longer than one hour; usually a plunger lift data set consists of more than 500,000 data points. After acquiring a large quantity of data it may be difficult to identify a key event. Identifying key events that occur during the plunger cycle will aid in the analysis of the data; the process of identifying a key event is called "annotating". To aid in the analysis of the plunger lift cycle it is recommended to annotate the key event while acquiring data. When a specific event occurs during the plunger lift cycle software allows the time of the event to be identified; events such as the exact time when the control valve opens or closes, the plunger starts to fall or gets stuck in the tubing, etc. Usually annotating is done while acquiring the data but annotating can be also done after the data acquisition is complete. **Figure 1** shows the tubing, casing pressures and acoustic signal for one plunger lift cycle where key events are identified and annotated on the figure. A key event such as the time when the plunger reaches the liquid at the bottom of the tubing is generally characterized by the disappearance of the tubing collars signals generated as the plunger passes through the tubing and by a large amplitude pulse followed by a change in the noise level. The events that are related to the opening and closing of the control valve are identified by rapid change in the pressure. A key event of the time when the plunger reaches the bottom of the tubing is generally characterized by a further reduction in the acoustic noise level, plus a slight increase in the tubing pressure. **Figure 2** illustrates key events during the Unloading and Afterflow period. These include the arrival of the liquid and plunger to the surface and are generally apparent both on the pressure and the acoustic signals, characterized by rapid changes in amplitude and slope of the traces. Liquid arrival at the surface is characterized by a sudden increase of the tubing pressure and the detection of significant noise amplitude on the acoustic signal. The arrival of the plunger at the surface can be identified as the point of peak tubing pressure while the motor valve is open. If liquid is above the plunger, the pressure spike always occurs and once the plunger arrives in the lubricator the tubing pressure rapidly drops as the gas is released into the surface flow line. If there is no liquid above the plunger, there may be a short duration slight increase in tubing pressure and a sharp noise on the acoustic data. The point where the tubing pressure begins to decline corresponds to the beginning of the afterflow period when gas is flowing through the open valve. Unexpected occasional events should be identified with a comment from the operator. Identifying specific key events that occur during the plunger lift cycle will help in the analysis of the collected data.

Monitoring Plunger Location

The digital fluid level instrument monitors and digitally records the acoustic and pressure signals from inside the tubing as a function of time. It has the sensitivity to acquire tiny signals from the gas gun microphone detecting pressure changes created by the plunger falling in the tubing. Usually an acoustic pulse is generated and tubing pressure fluctuation occurs when the plunger falls through a tubing collar recess. The tubing carries the weight of the plunger when the plunger is resting at the bottom or mechanically held at the surface by a catcher, but during the remaining time of the cycle the weight of the plunger is applied to the gas or fluid in the tubing. A difference in pressure exists across the plunger; this pressure difference is approximately equal to the weight of the plunger divided by the tubing area plus or minus other minor factors. This difference in pressure above and below the plunger is usually in the range of 14 to 20 kPa (2 to 3 psi) in pressure. **Figure 3** shows the beginning of the shut-in period where a sudden drop in tubing pressure is caused by the weight of plunger suddenly acting on tubing gas at the beginning of the plunger fall. The figure on the right shows a gradual increase in tubing pressure and a sudden drop in pressure when the plunger's fall begins; this trace is representative of plunger installations where the gas pressure holds the plunger at the surface during the afterflow time period. The figure on the right shows a sudden drop in tubing pressure when the plunger was released from the catcher. The tubing pressure will also suddenly increase when the plunger suddenly stops in a tight spot in the tubing or stops on a dry bumper spring. As the plunger falls through a tubing collar a pressure wave is generated as each tubing collar recess temporally carries a portion of the plunger weight. When the tubing temporally holds the weight of the plunger, then the pressure above the plunger rapidly increases. This acoustic pulse, which is generated at the tubing collar recess, travels through the gas to the surface and is detected by the microphone and also by 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. **Figure 4** shows a portion of the acoustic and pressure records during 0.2 minutes during the shut-in time period. The record shows that a 0.1-psi amplitude pressure wave and an acoustic signal are generated as the plunger fell past the 112th tubing collar recess at a depth of 3444 feet**.** These signals created by the plunger falling past each tubing collar recess are monitored at the surface so that the plunger travel is followed on a continuous basis. Periodic firing of the gas gun is not required to determine the position of the plunger by echo ranging. The method of acoustically recording plunger generated pressure waves from the tubing collar recess has been defined as "passive" monitoring of the plunger position during the fall. The schematic for the instrumentation set up is shown in **Figure 5**, with pressure sensors connected to both the tubing and casing. For passive monitoring, high frequency (30Hz or greater) data acquisition is used to record the signals from both tubing and casing pressure sensors, plus the acoustic signal from the microphone.

When the plunger enters the liquid the fall is slower than in gas, the tubing recess acoustic pulses are generally difficult to identify when transmitted through the liquid. Usually a decrease in the acoustic noise level indicates that the plunger is submerged in the tubing liquid. The field acquired acoustic and tubing pressure data in **Figure 6** shows tubing collar recess echoes both in the gas above the liquid and lower frequency echoes from the collar recesses below the liquid level. Usually when the tubing pressure is high (greater than 2700 kPa) it is possible to see acoustic pulses as the plunger falls through the liquid. When the plunger finally rests on bottom on the bumper spring the noise level drops again and a small increase in tubing pressure is observed, and the time when the plunger reached bottom may be determined with certainty.

Monitoring of tubing and casing pressure simultaneously with the acoustic signals can precisely identify timing of various key events during the operation of the plunger. The variation of pressure during the cycle is then used to calculate volumetric flow of gas from the reservoir into the well and from the well to

the flow line. The objective of these calculations is to present an analysis of the performance of the plunger system in terms of gas and liquid production per cycle in order to optimize the operation of the system.

Analysis

The process to analyze the collected plunger lift data includes four steps: 1) Select the Plunger cycle to analyze, 2) Identify Key events in the selected cycle, 3) Determine plunger fall velocity, 4) Determine the gas gravity.

1) The purpose of this step is to select one complete cycle from the total sequence of data that was recorded. A time period is selected to identify the beginning and end of a complete plunger cycle from the collected set of data. The cycle may start at the beginning of shut-in or at the start of the flow period and continue until the following cycle, which are valve-opens to valve-opens or valve-closes to valve-closes.

2) Key events are identified during the selected cycle. During the Shut-in time period identify within the plunger cycle the times when the following two key events take place:

1. Plunger hits Liquid
2. Plunger on Bottom

During the Unloading and Afterflow Period identify within the plunger cycle the times when the following two key events take place:

1. Liquid Arrives to surface
2. Plunger arrives to surface

3) Determine plunger location during the shut-in time period by identifying and counting tubing collar signals as the plunger falls past each tubing collar recess. Identification of these signals is used to determine the plunger position and fall velocity vs. time.

4) The gas gravity is required to compute the volume of gas in the tubing and casing, plus the pressure at the bottom of the tubing and casing. Gas properties may be input or determined by processing the acoustic signal of the plunger fall. After steps 1-4 are completed, then a complete analysis of the plunger lift system can be performed.

Plunger Fall

In the record for the shut-in period, each tubing collar echo is identified and counted to determine how fast the plunger falls and determine if it falls to the bottom. The location in time of the tubing collar recess echoes determines the speed and depth of the plunger. If the acoustic signals generated by the plunger are clearly visible on the acoustic trace, then software is used to automatically identify and record the time of occurrence of each acoustic collar recess pulse and count all the tubing joints that the plunger has traversed. Using the plunger depth and the elapsed time then the plunger fall velocity is computed and a graph of the position of the plunger and plunger velocity vs. time is generated.

Figure 7 displays the acoustic record beginning at a time of approximately 8.9 minutes after data acquisition began. The graph at the lower left is a representation of the acoustic signal recorded from the start of the shut-in period [A] until the marker [1] when the plunger hit the liquid near the bottom of the tubing. Note that in the lower left window the vertical white band is the 1-minute interval of the acoustic trace plotted at the top of the figure. The signal at 9.361 minutes in the upper trace corresponds to the time when the plunger fell past 44th the tubing collar recess at a depth of 1416.8 feet. The user may manually identify all the pulses that correspond to the plunger falling past the tubing collars or the collars may be automatically selected after the software has been "trained" to properly identify these signals. The times are marked with a line when the plunger fell past collar 44 (labeled C44 at 9.361 minutes) and when the plunger reached the next tubing collar (labeled C45 at 9.514 minutes). Using the well's average joint length of 9.81 m/joint (32.2 feet/joint), the fall velocity of the plunger is computed to be 63.78 m/min (–209.24 ft/min). (Negative sign indicates falling down the tubing and positive indicates the plunger rising in the tubing). After some of the collar recesses are counted, the plunger fall velocity past each collar is determined and the speed and depth of the plunger as a function of time is computed. How fast the plunger falls to the bottom during the shut-in period in shown at the bottom of the figure; the average fall velocity through gas is 51.3 m/min (–168.3 ft/min) and the average fall velocity through the liquid is 11.89 m/min (–39.0 ft/min). In the lower right corner, the table displays the time, plunger velocity and depth values that correspond to the movement of the plunger past ten previously identified collars.

Plunger Fall Velocity and Depth Graph

Figure 8 is used for quality control of the analysis process since it represents the position of the plunger and its instantaneous velocity to the depth where collars have been counted.

The general trend of the plunger fall velocity is to consistently slow down as time (plunger depth) increases. When liquid is present in the bottom of the tubing trapping the gas in the tubing, it is normal for the plunger fall to initially start fast and gradually slow down as the plunger gets deeper into the well. Significant deviations from this trend would be an indication that the identification of the collar signals should be reviewed/verified OR that there may be a problem with the operation of the well. An operational problem may exist in the well if the plunger falls at a constant speed or slows down and speeds up during its fall.

Figure 8 shows, at the top, that collar #2 has been selected (by manually locating the vertical dotted line using the software buttons) where the plunger is only 19.63 m (64.4 ft) from the surface showing that the fall velocity is –77.7 m/min (–255 ft/min) at that point. When the plunger hit the liquid the fall velocity had decreased to 41.3 m/min (–135.4 ft/min). The elapsed time for the plunger to fall from the surface to the liquid level in the tubing was 45.2 minutes. This time also corresponds to the plunger being at a depth of 2229 m (7313.2 ft), based on the average tubing joint length determined for the well. The plunger fell through the gaseous liquid column in the bottom of the tubing at a rate of 11.9 m/min (–39 ft/min) and fell from 2229 to 2369 ft (7313.2 to 7773 ft) in 11.8 minutes. Plungers fall much slower in a gaseous liquid in the bottom of tubing than in gas.

Plunger fall velocity that deviates from the general trend (gradually slowing down with depth) is easily identified by examination of the plunger fall trace. The corresponding collar reflections can be examined in more detail on the acoustic trace by double clicking a point of interest on the graph. A detailed discussion[3] of the various methods that may be used for monitoring the plunger position during the shut-in periods is found in the paper: SPE 80891.

Gas Properties

The specific gravity of the produced gas must be determined to accurately calculate the pressure distribution in the tubing and casing and calculate the volumetric rates of gas inflow from the reservoir. Properties of gas sampled at the sales line or even at

the separator, generally are not necessarily representative of the properties of the gas within the annulus or the tubing. The best estimate of the gas gravity will be obtained from measurements while tracking the plunger fall. At a certain pressure and temperature the acoustic velocity in a gas is directly related to its specific gravity. This relationship is used compute the gas gravity when the gas acoustic velocity has been determined. Shooting the liquid level in the tubing during the shut-in period makes a direct estimate of acoustic velocity. Most often it is not necessary to shoot a fluid level, since acoustic velocity in the tubing gas can be computed by analyzing the signals generated as the plunger falls past the tubing collars.

The acoustic velocity of the tubing gas can be computed by analyzing in more detail the acoustic signals generated by the plunger as it falls past the tubing collars. An acoustic pulse that is generated when the plunger goes past a collar propagates via the gas in the tubing above the plunger to the wellhead (where it is detected by the microphone) and then is reflected back down through the gas until it reaches the top of the plunger and is reflected back to the surface where the microphone detects it as a first echo. Since the acoustic velocity in the gas is in the range of 427 m/sec (1400 ft/sec) for low pressure methane gas and the plunger velocity is much slower, in the order of 60-300 m/min (1 to 5 m/sec) [200-1000 ft/min (3.3 to 16 ft/sec)], the plunger has not fallen a significant distance by the time the acoustic pulse catches up with the plunger and is reflected back to the surface. This reflection process is repeated several times before the plunger reaches the next collar. **Figure 7** shows that collar C44's echo occurs at 9.361 minutes and its repeat echo (marked with the vertical dashed line) occurs 2.21 seconds later. The depth to collar C44 is 432 m (416.8 ft) and the repeat echo traveled from the microphone to the top of the plunger and back to the microphone in 0.0368 minutes. For this round trip travel time the acoustic velocity calculates to be 391 m/sec (1282.1 ft/sec) and the corresponding gas specific gravity calculates to be 0.724.

In some cases, due to the noise level in the wellbore or other plunger characteristics, it may not be possible to identify the multiple reflection signals. The user then should retrieve the gas gravity that was computed from the acoustic velocity when a conventional fluid level survey was done in the tubing during the shut-in period and enter this value in the calculation form.

Cycle Analysis

The analysis begins either at the beginning of the Shut-in period (motor valve closes) or at the start of the Unloading period (motor valve opens**). Figure 9** provides a complete analysis of the plunger cycle and a detailed summary of the pressures and volumes flowing into and out of the well as a function of the plunger position. The average producing bottom hole pressure is calculated and is compared to the static bottom-hole pressure. Vogel's IPR relationship is used to determine the well's inflow performance efficiency and the maximum obtainable gas and liquid flow rates.

On the right of **Figure 9** the wellbore schematic shows the position of the plunger as well as the position of the tubing intake in relation to the formation depth. The Plunger Lift Operational Cycle is displayed at the top left side of the wellbore diagram. This indicates the section of the plunger lift cycle that is being displayed depending on the previous analysis: 1) Shut-in, 2) Unloading, or 3) Afterflow.

At the lower left is a slider control that is used to step through the complete plunger cycle. The display of the position of the plunger changes when selecting a particular time during the cycle using the slider, the software displays the measured and computed values dependent on elapsed time. Clicking on the Auto-Step button animates the figure and results with the plunger moving up and down the tubing at equal time steps through out the cycle. **Figure 9** shows the instantaneous conditions during the Shut-in cycle when the plunger has fallen to a depth of 2097 m (6880 ft) from the surface and is located about 97 m (318 ft) from the top of the gaseous liquid at the bottom of the tubing.

Following are definitions of the various quantities displayed:

Surface Pressure Tubing: This is the tubing head pressure measured at the specific time selected during the cycle.

Surface Pressure Casing: This is the casing head pressure measured at the specific time selected during the cycle.

Tubing Pressure Buildup: psi/min: This is the rate of change in tubing head pressure as a function of time when the motor valve is closed, expressed in psi per minute.

%Liquid: Is the computed percentage liquid in the gaseous liquid column at the bottom of the tubing calculated based on the tubing pressure buildup[5].

Gaseous Liquid Level: is the depth to the top of the gaseous liquid column at the bottom of the tubing.

Liquid Level (Gas Free): is the measured depth to the top of an equivalent gas-free column of liquid in the tubing.

Gas Flow: displays the instantaneous gas flow rate in Mscf/D, or cumulative volumes in Mscf, calculated from material balances in the annulus and the tubing at the time corresponding to the displayed plunger position. The following instantaneous flow rates are displayed: 1) Formation: gas rate of flow from the formation, 2) Casing: gas rate of flow from the casing, 3) Tubing effect: gas rate of flow from the tubing, 4) Flow Line: gas rate of flow from the well into the flowline

The user can select to display cumulative produced gas volumes values by clicking on the units field and selecting the values of cumulative per plunger cycle or cumulative per day.

Assuming all of the liquid accumulated at the bottom of the tubing, prior to unloading, is produced to the surface, then 1) Liquid Production STB/Cyc: displays the total liquid produced per plunger cycle, and 2) Liquid Production STB/D: displays the total liquid produced per day assuming that each cycle produces the same volume of liquid.

Liquid at Bottom of Tubing: displays the volume of liquid at the bottom of the tubing as a function of time in Bbls or height of gas-free liquid.

Tubing Intake Pressure: this is the pressure in the annulus calculated at the depth of the tubing intake (depth to bumper spring).

PBHP: This is the calculated producing bottom-hole pressure at the datum depth. The PBHP changes throughout the plunger lift cycle.

Reservoir Pressure (SBHP): This is the shut-in BHP as entered in the well data file.

The information on this schematic diagram is a complete representation of the well's operating conditions at times selected by the user during the complete plunger cycle.

The top left-hand side of the Cycle Analysis Tab shows the current oil, water and gas daily flow data from the most recent production test as entered in the well data file. This information is used in subsequent calculations of well performance and should be as recent and as accurate as possible.

The Potential is the maximum daily production if the producing pressure (PBHP) were reduced to zero. It is computed using the selected IPR Method for representing the well's performance: (Productivity Index or Vogel IPR).

PBHP/SBHP-This is the ratio of the current producing bottom-hole pressure to the shut-in bottom-hole pressure. A value of 1.0 corresponds to a shut-in well. A value of zero corresponds to a well producing at open flow or maximum production rate.
Producing Efficiency - Expresses the current well test flow rate as a percentage of the calculated potential maximum flow rate. It is very important that the well data be accurate, because the program calculates bottom hole pressure and calculates the plunger's performance analysis using all these values.

At the bottom left of the window is a time line corresponding to the plunger cycle that has been analyzed. The timeline shows the sequence of operational cycles, the time (hh:mm:ss) when the plunger cycle started and when it ended as well as the start time of each operation. The duration (mm:ss) of each operational cycle is also displayed. The slider bar allows the operator to move through the plunger cycle to display the position of the plunger and view the variation of the flow and pressure variables. The Step Increment is defaulted to 60 seconds/step but may be changed by the user to a more convenient value by entering a different time step in seconds.

Analysis Plots

The software provides the user the ability to plot a large number of diagnostic graphs to aid in further analysis of the plunger cycle or to identify problems that may not be apparent from the routine analysis. Two variables may be plotted as a function of elapsed time on the horizontal axis. The values discussed in the Cycle Analysis section that change as the user steps through the plunger cycle can be plotted and compared to each other. In **Figure 10** the numeric values of the two variables are displayed in the boxes at the lower right, for the time corresponding to the position of the vertical dashed line indicator which is positioned with the Left and Right buttons or directly positioned by pointing and clicking on the point of interest on the signal trace. Plots can be viewed in greater detail by using the zoom feature to change the elapsed time range of the horizontal axis. The analysis plots display the data at a default step increment of 60 seconds. If a more detailed investigation is required an increment of 5-15 seconds is usually best for the display of the plunger lift data.

Figure 10 displays the cumulative production from the formation and the instantaneous gas flow rate down the flow line computed from the measured pressures, gas properties, and height of the gas free liquid in the tubing, plus the wellbore configuration. Gas flow from the formation occurs during the entire cycle whether the flowline valve is open or closed and the increase in cumulative volume from the formation is steeper at the low flowing bottom hole pressure after the plunger arrival shown by the vertical dashed line indicator line. Generally there are two peak instantaneous gas flow rates down the flow line, one peak occurs at the beginning of the unloading period when the flow line valve is first opened and a second peak gas flow rate occurs at the beginning of the afterflow period immediately after the plunger arrives at the surface. These two peak rates are typical of the flow regime occurring at the time when the flow line valve is open. The initial high gas flow rate is due to gas stored in the tubing above the plunger and the second high gas flow rate is due to gas accumulated behind the plunger which lifted the plunger and liquid to the surface.

Operational Problem Examples

Figure 11 shows a common problem in plunger lifted wells. As the pressure builds during the shut-in period, the liquid in the tubing is often pushed out and the plunger hits dry tubing when arriving at the bottom. Hitting dry is a problem because the gaseous liquid normally slows the plunger fall; hitting dry can result in damage to the plunger, bumper spring and downhole assembly. To alleviate this condition a standing valve is used to hold the liquid in the tubing during the shut-in time period. At the start of the shut-in period (leftmost dashed vertical marker) the difference between the tubing and casing pressure indicates that liquid had entered the tubing at the end of the afterflow time period. At an elapsed time of approximately 28 minutes on the horizontal axis the vertical dashed line shows the time where all the liquid being held in the tubing had been pushed from the tubing and the only difference in casing minus tubing pressure is due to the weight of the falling plunger. Another indication that all of the liquid was pushed from the tubing is the tubing and casing pressure equalize at approximately 55 minutes when the plunger landed on the dry bumper spring at bottom.

Figure 12 displays how pressure equalizes between tubing and casing in a typical stair step fashion when a standing valve is installed in a plunger lifted well to prevent liquid from being pushed out of the tubing. Notice how the tubing pressure suddenly increases when the standing valve opens and gas enters the tubing and then remains constant while the standing valve is closed and no gas is entering the tubing. The tubing pressure increases in approximate 2.7 kPa (0.4 psi) steps as the standing valve opens and closes at the end of the shut-in time period. The pressure difference between the casing pressure and the tubing pressure remain constant, indicating that all of the liquid is being held in the tubing by the standing valve. Measurement of this stair-step action of the tubing pressure is a simple means to verify that the standing valve installed in a well is functioning properly.

Figure 13 shows the effect of a hole in the tubing on the plunger fall velocity. The plunger falls at a nearly constant velocity of 66 m/min (217 ft/min) from the surface to the hole. Once the plunger falls past the hole at 1540 m (5051 ft) from the surface, then the trapped gas between the plunger and the liquid at the bottom of the tubing result in the plunger gradually slowing down to a fall velocity of 61 m/min (200 ft/min). In this well a 0.05 cm (1/8 in) diameter hole in the tubing was located in the 156th tubing joint from the surface. During the unloading period of the cycle the presence of a hole was causing the plunger to not arrive at the surface 80% of the time.

Figure 14 shows the tubing pressure behavior when the plunger falls past a hole in the tubing, where the hole is above the liquid in the bottom of the tubing. In this example the tubing and casing pressure at the surface and at the hole are equalized due to a hole through the tubing. When the plunger began the fall the gas pressure in the tubing below the plunger was increased by the weight of the falling plunger and the increase in pressure below the plunger forced pressure out of the hole slightly raising the casing pressure. When the plunger falls past the hole then the higher gas pressure from casing equalizes back into the tubing, thereby equalizing the tubing and casing pressure at the hole. The plunger falls past the hole at a depth of 549 m (1800 ft) from the surface and the point where tubing pressure begins increasing is used to identify the depth of the hole. When trouble-shooting tubing for a possible hole; the tubing must have some liquid in the bottom to trap the gas between the plunger and the liquid, only then can the tubing pressure increase can occur when the plunger falls past the hole.

Figure 15 shows the plunger suddenly stopping as it was falling to bottom during the shut-in period of the cycle. In this example the plunger had fallen 569 (1866 ft) from the surface and the sharp 20 kPa (3 psi) increase in the tubing pressure at

this depth indicates that the plunger is stuck in the tubing and the tubing gas pressure is no longer depressed by the weight of the plunger. Three minutes after the plunger began the fall the operator identified that the plunger was stuck and began corrective measured to unstick the plunger.

Figure 16 shows the impact of reduced gas production due to having the shut-in time set for too long of a period. The initial 68 minute shut-in time period of the plunger cycle is displayed. Long shut-in time resulted in fewer cycles per day and in large liquid loads during the unloading cycle with an average plunger rise velocity of 177 m/min (580 ft/min). The initial afterflow period lasted 70 minutes and during shut-in the plunger fell to the liquid level in 30 minutes and the plunger rested on the bumper spring for almost 30 minutes. Based on the plunger resting on bottom for too long of a time period, **Figure 17** shows that the shut-in period was decreased from 68 minutes to 33 minutes. The shorter shut-in time period resulted in an increase in gas production from 4750 to 6820 m3/d (168 to 241 MscfD) and condensate production increased from 1 to 1.3 m3/d (6 to 8 BPD). The shorter shut-in time period also resulted in an increase in the plunger rise velocity close to 305 m/min (1000 ft/min); afterflow time should be lengthened to reduce system pressure, to bring more liquid into the tubing and decrease the plunger unloading speed.

Conclusions

Troubleshooting plunger lift operational problems become much easier when the plunger depth and fall velocity are known.

1. Plunger fall velocity can be accurately measured with an acoustic instrument,
2. Minimum shut-in time for the plunger lift installation can be determined.
3. Plunger fall measurements will ensure that the plunger will fall through the fluid at the bottom of the tubing and be resting on the bumper spring by the end of the shut-in period.
4. If a plunger becomes stuck is easily identified and corrective measured can be taken to fix the problem.
5. Holes in the tubing are identified by observing changes in the plunger fall velocity and in the tubing pressure.

Monitoring the complete plunger cycle with a new portable monitoring system is a fairly simple task. By accurately measuring the plunger fall velocity and depth to the liquid level, then the minimum shut-in time for the plunger lift installation can be determined. The plunger fall measurements ensure that the plunger will reach the bottom of the tubing by the end of the shut-in period. Maximum production from the plunger lift installation will be obtained by having the shortest possible shut-in time.

The new portable monitoring system minimizes the need for using a wire line. A plunger can be dropped and tracked to the seat nipple or collar stop. The tubing collar recesses can be counted to be sure the plunger has arrived at the bottom. The operator will save time by quickly identifying holes and eliminating the need to drop standing valve and pressure test the tubing. The new portable monitoring system increases safety of plunger lift operations by knowing where the plunger is in the tubing. If a plunger is not going to bottom and the well is pressured up, then the plunger could surface dry at a very high velocity. Plunger arrival at high velocity can cause equipment damage and could result in exceeding the mechanical integrity limits of the lubricator. Development of a new portable monitoring system has taken the guesswork out of plunger lift analysis, troubleshooting and optimization. Having a detailed analysis of the operation of the well makes optimization of plunger lift production achievable with a minimum of effort and avoids the usual waste of time due to trial and error procedures.

NOMENCLATURE

BPD	=	Barrels per Day
STB/Cyc	=	Stock Tank Barrels per Cycle
MscfD	=	1000 Standard Cubic Feet per Day
PBHP	=	Producing Bottom Hole Pressure
SBHP	=	Static Bottom Hole Pressure

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3. Rowlan, O.L., McCoy, J.N., and Podio, A.L, ”Determining How Different Plunger Manufacture Features Affect Plunger Fall Velocity” SPE 80891, presentation at the SPE Production and Operations Symposium held in Oklahoma City, Oklahoma, U.S.A., 23–25 March 2003
4. Phillips, Dan and Listiak, Scott, “How to Optimize Production from Plunger Lift Systems,” World Oil, April 1998 presented at the Southwestern Petroleum Short Course, Lubbock, Texas, 1997.
5. McCoy, James N., Podio, Augusto, L. and Huddleston, Ken L., “Acoustic Determination of Producing Bottomhole Pressure,” SPE 14254, presented at the 1985 SPE Annual Technical Conference and Exhibition, Las Vegas, Nevada, September 22-25, 1985.

Table 1

Plunger Lift Survey Answers Well Performance Questions:

1. Where is the plunger? On bottom? In or above liquid? Surface?
2. What is the depth to the top of the liquid in the tubing?
3. What are the producing and static BHP’s?
4. Is liquid in the casing annulus above the tubing intake?
5. What are the casing and tubing pressures during the operational cycle?
6. Does tubing gas/liquid pressure push liquid out of tubing?
7. What is the maximum production rate available from the well?
8. What is the gas flow rate? From Formation? Annulus? Flowline?
9. What is the gas gravity?
10. Are there restrictions to plunger fall in the tubing?

Figure 1 - Annotating Key Events during a Plunger Cycle

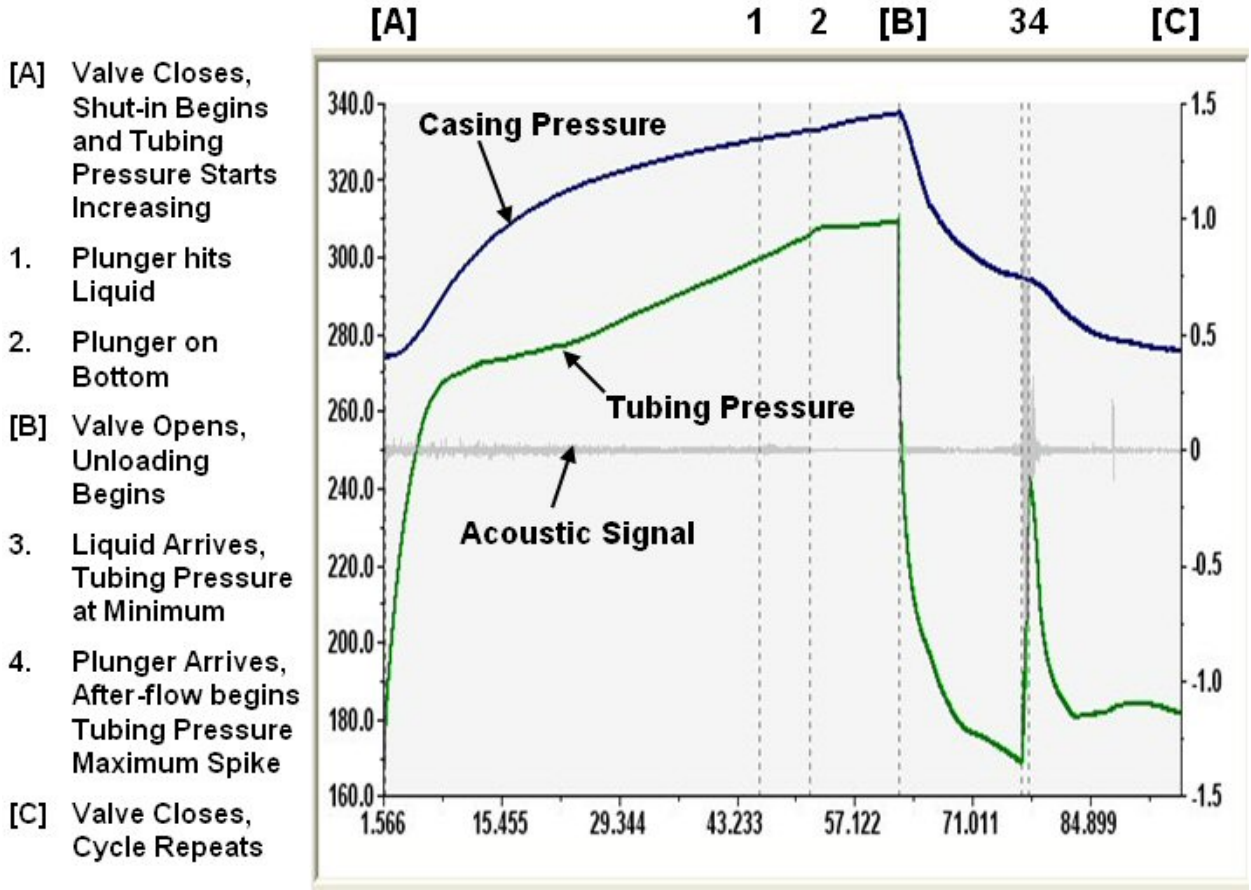

Fig. 2 Description of Key Events during the Unloading and Afterflow Period

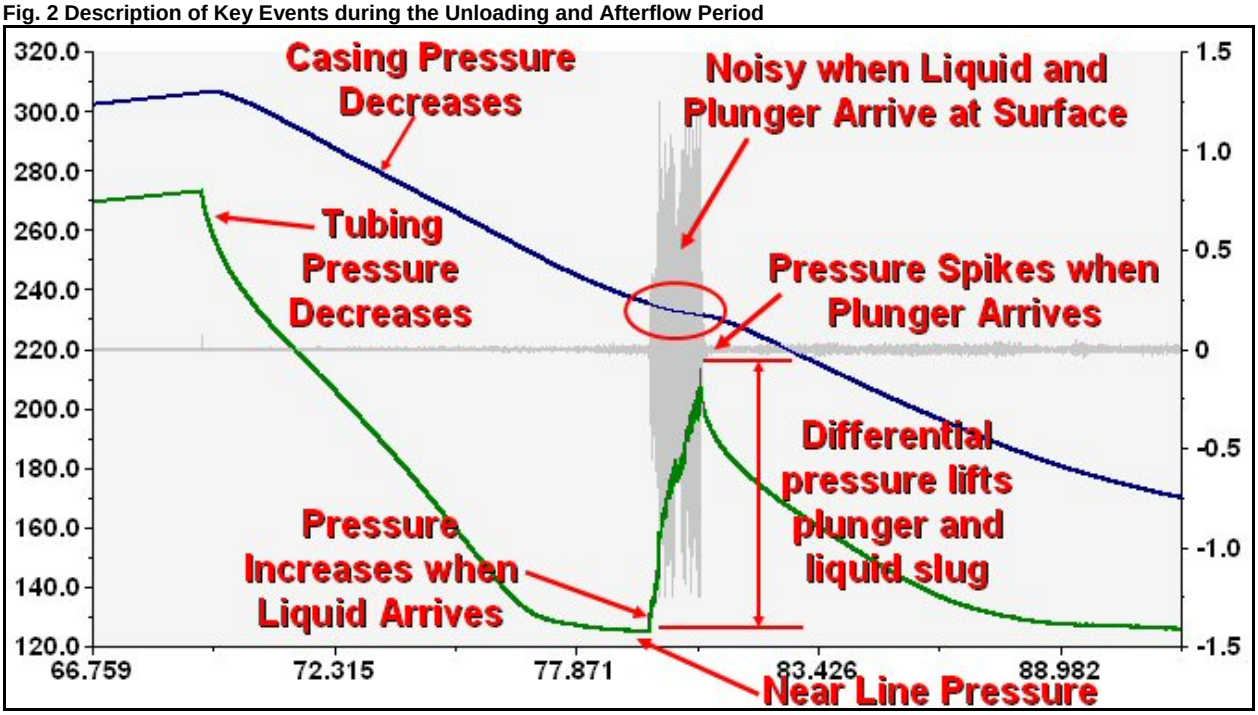

Figure 3 – Change in Pressure Due to Weight of Plunger Acting on Tubing Gas

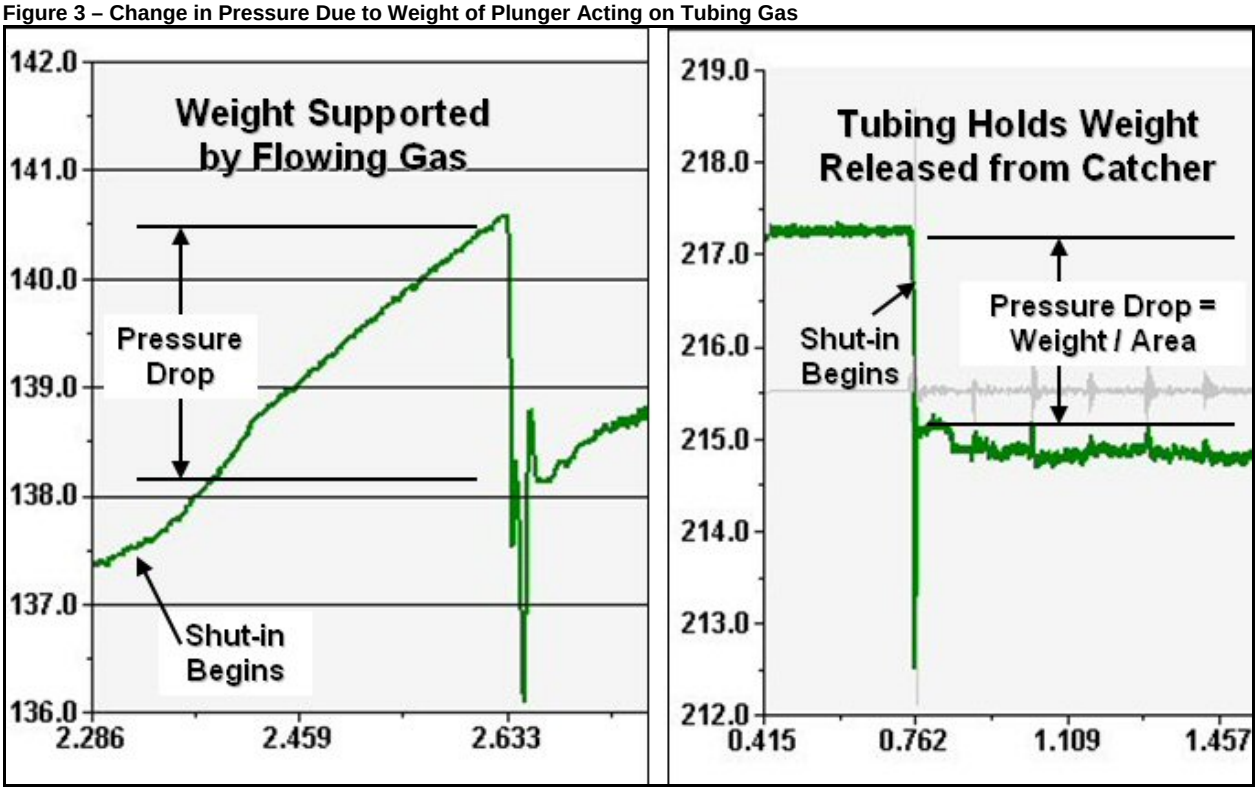

Figure 4 – Acoustic Signal from 112th Tubing Collar Recess

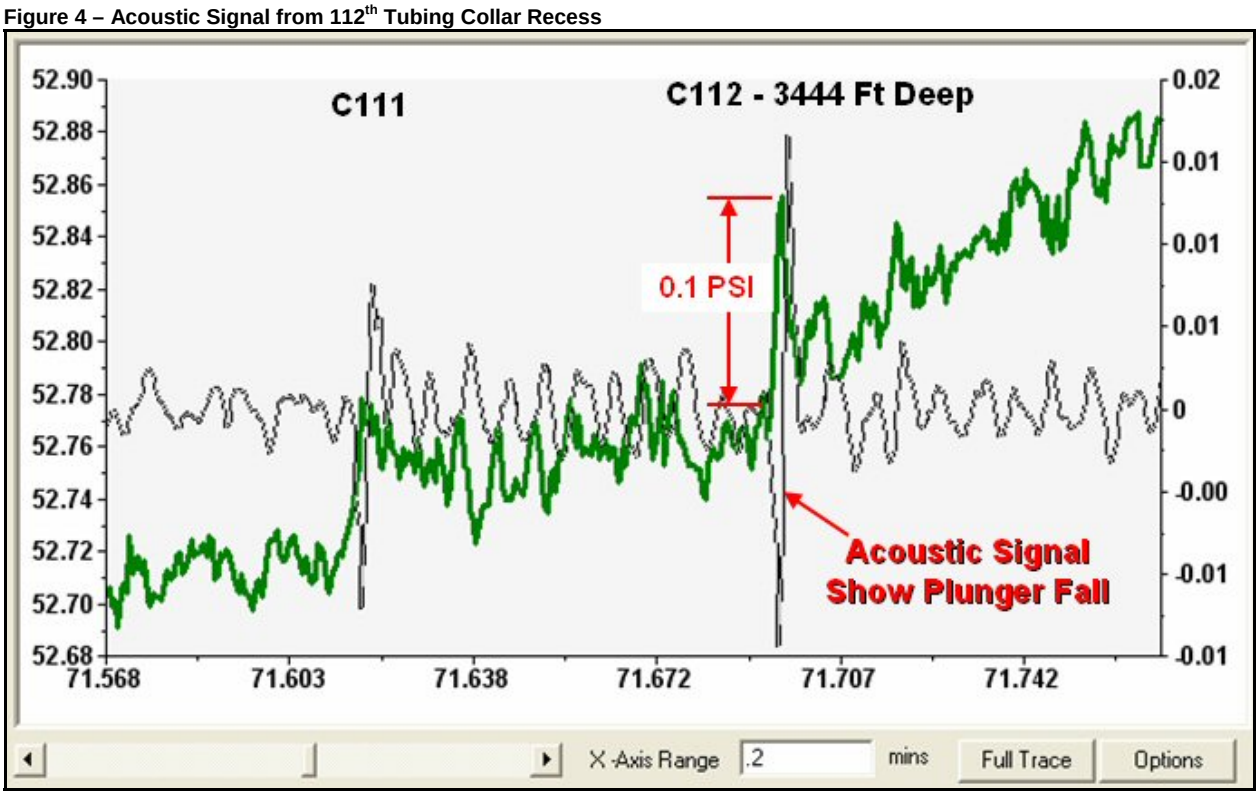

Figure 5– Passive Data Acquisition Configuration

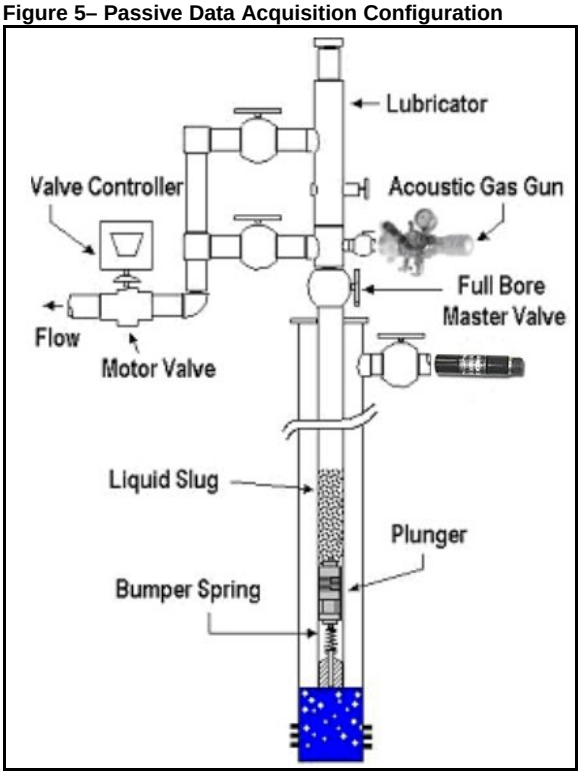

Figure 6 – Tubing Collar Recess Echoes Above and Below Liquid Level

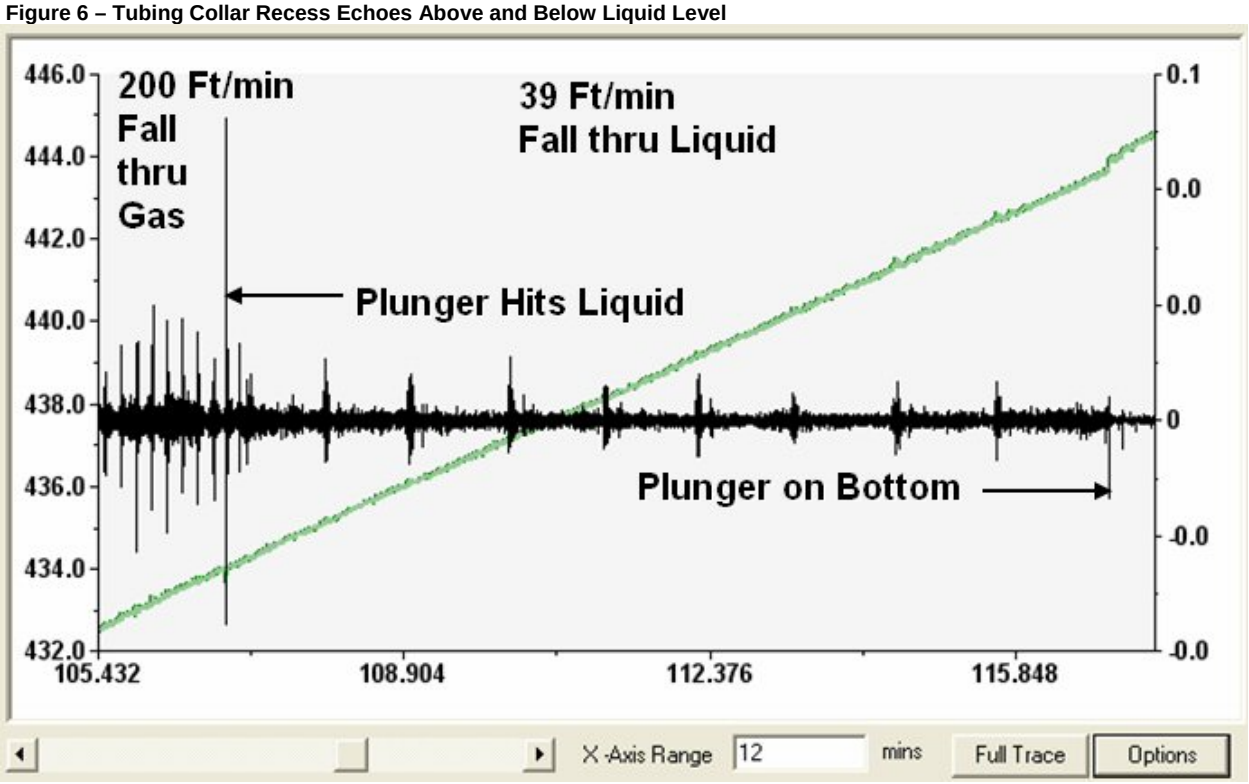

Figure 7 – Determining Plunger Fall Velocity and Depth

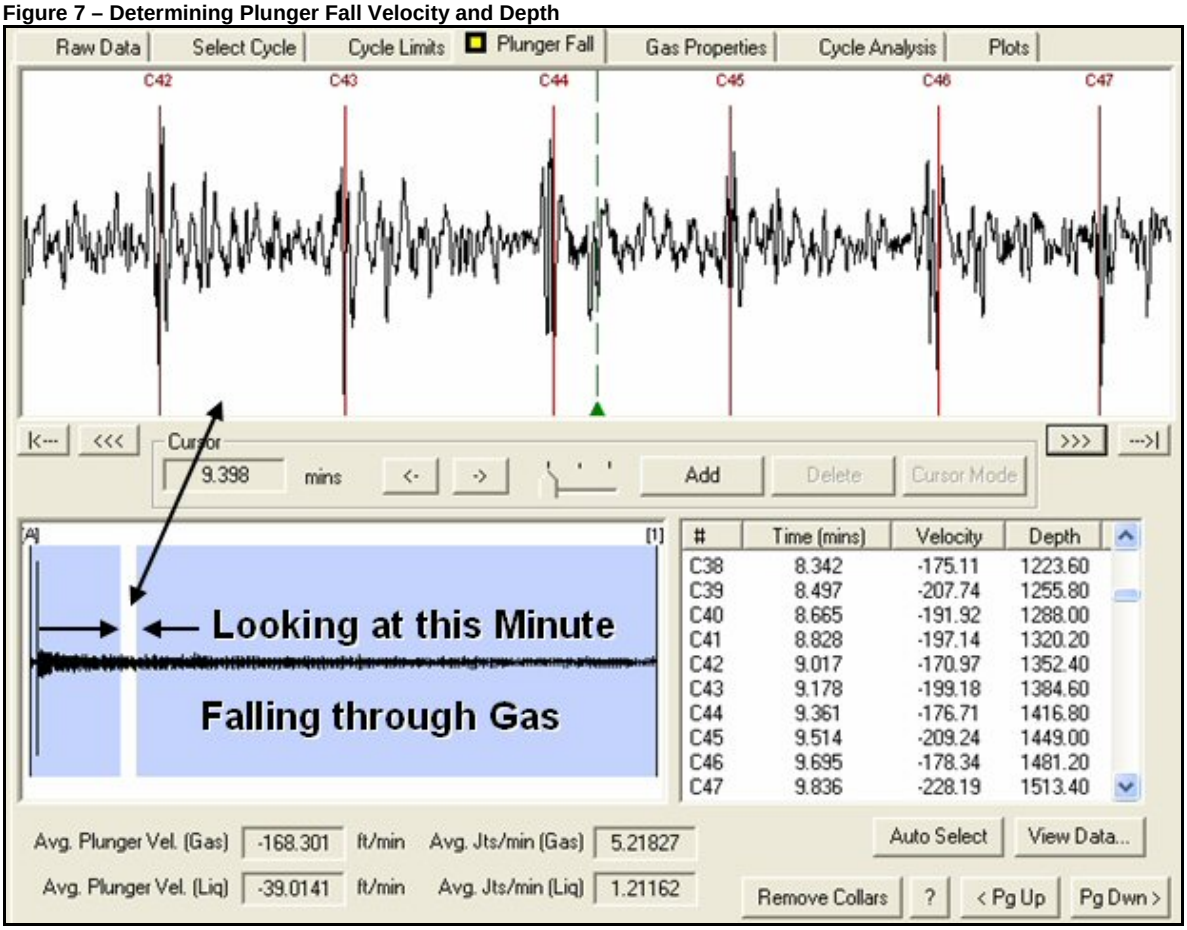

Figure 8 – Plunger Fall Velocity and Depth

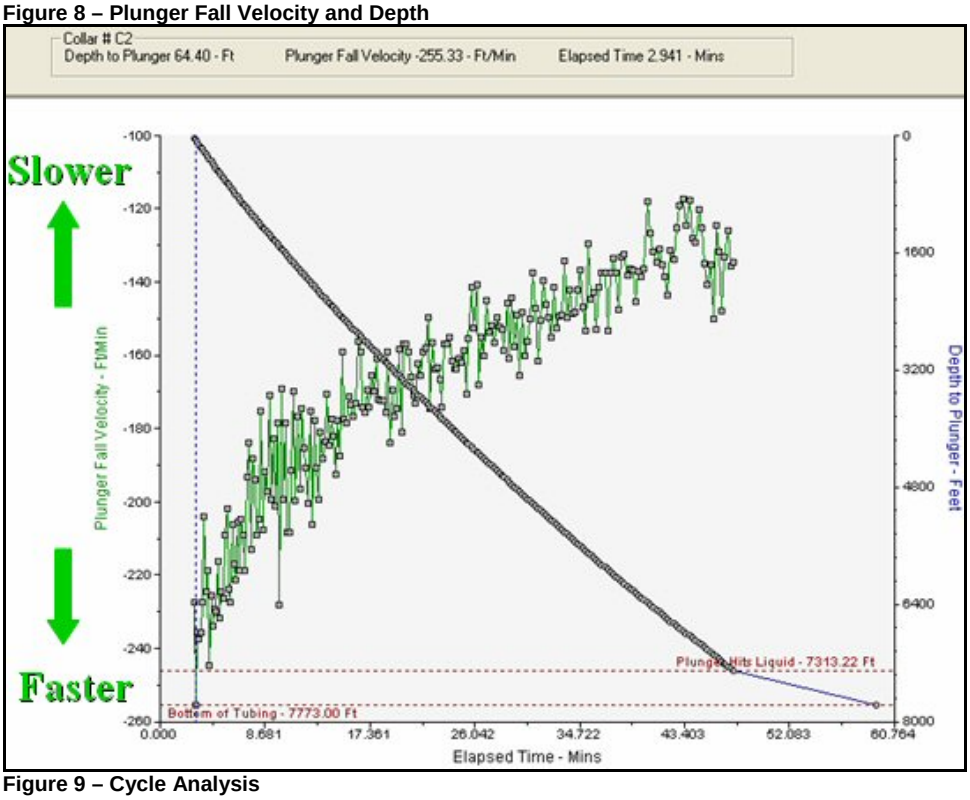

Figure 9 – Cycle Analysis

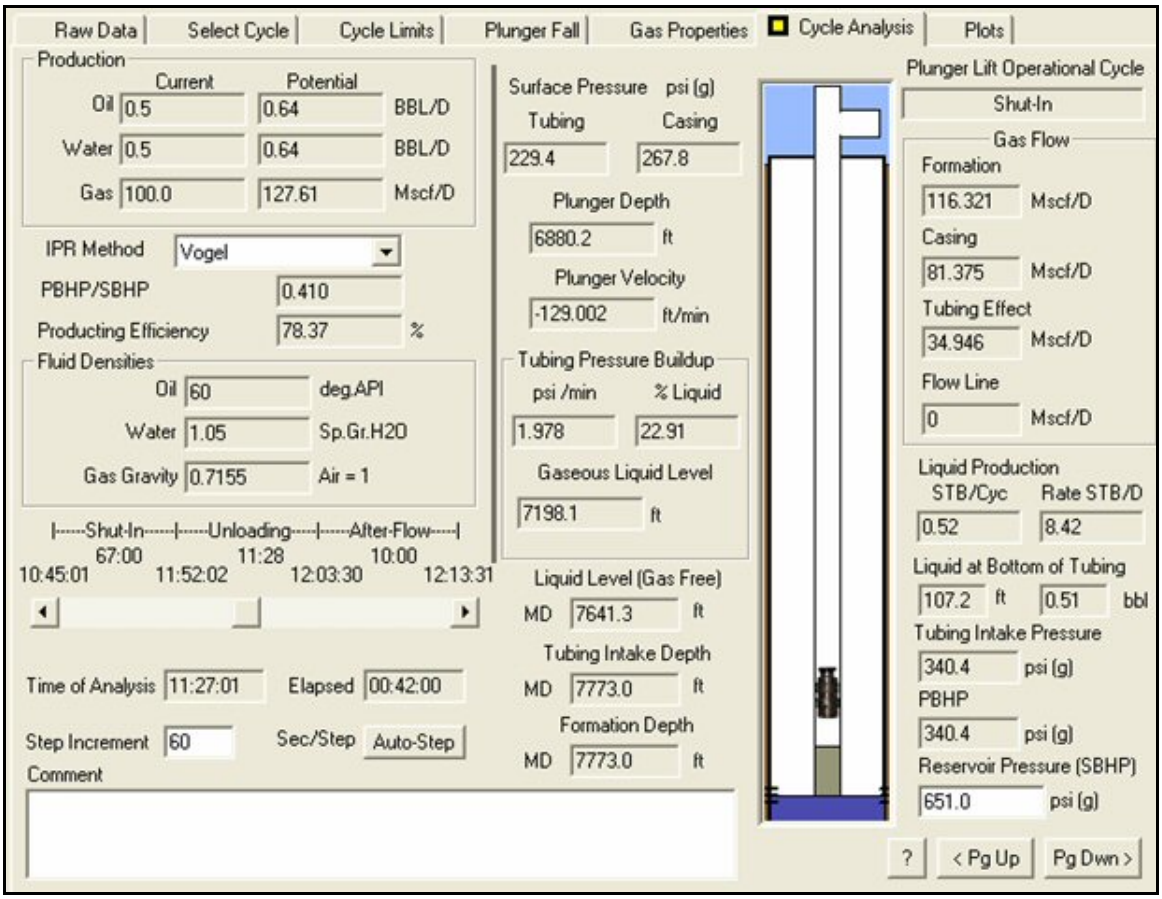

Figure 10 – Cumulative Gas Produced from Formation and Gas Flow Rate into Flow Line

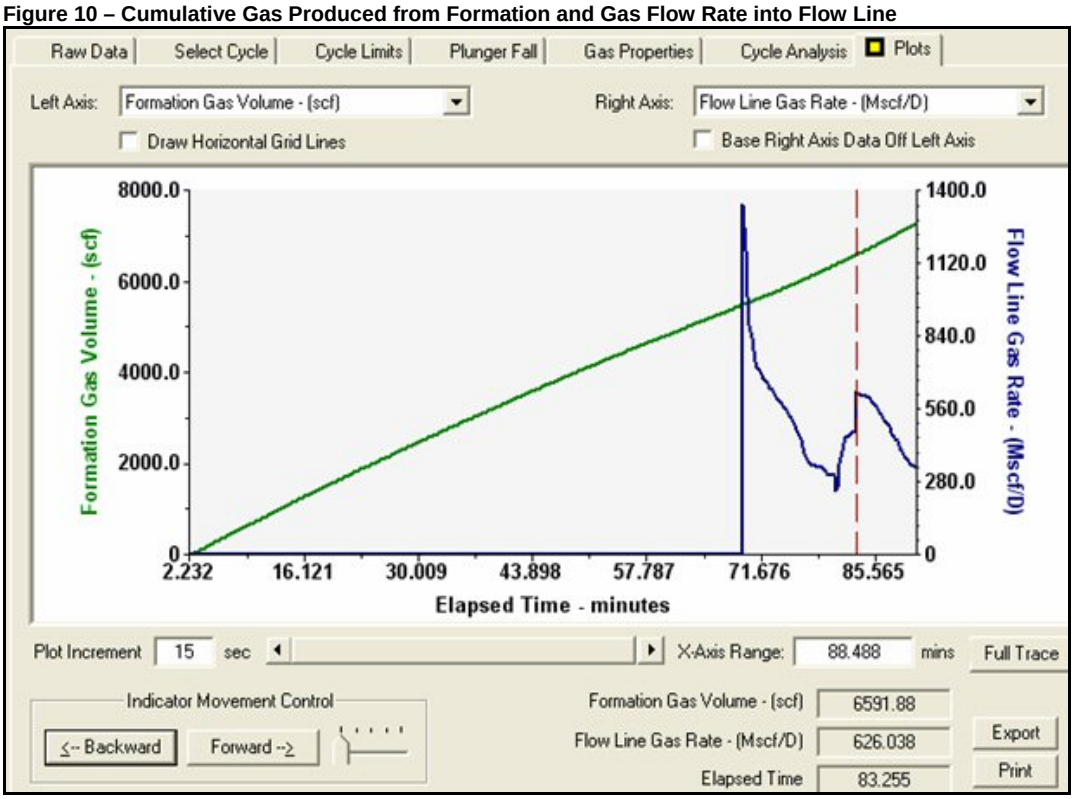

Figure 11 – During Shut-in Liquid Pushed out of the Tubing

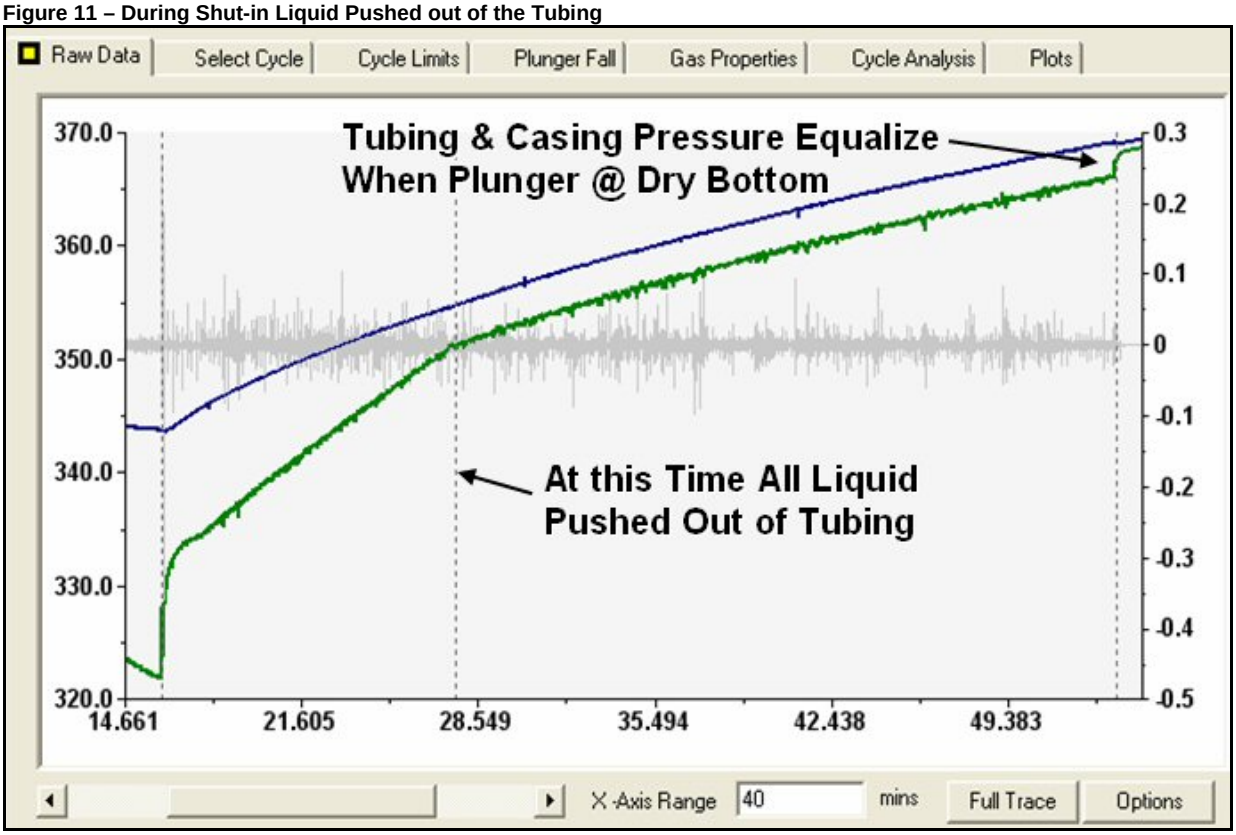

Figure 12 – Plunger Falls Past Hole in Tubing during Shut-in Period

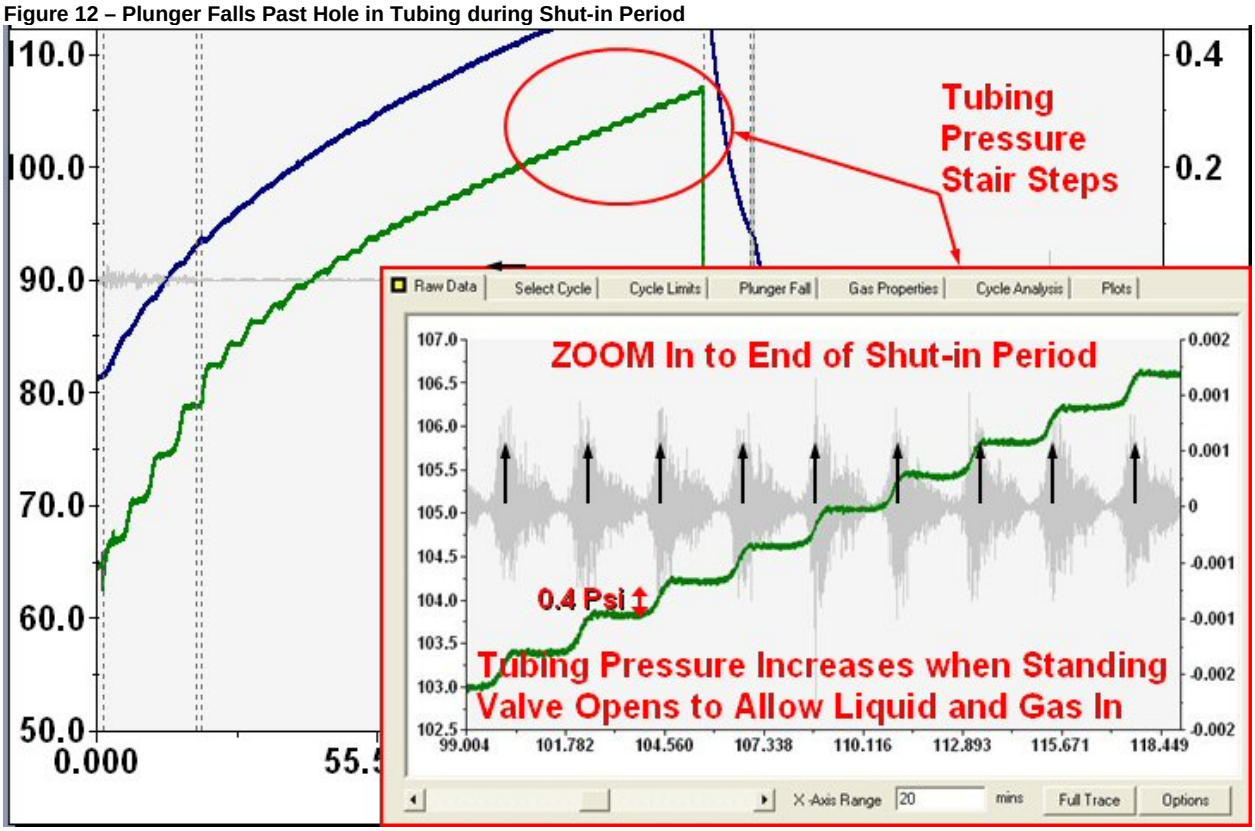

Figure 13 – During Shut-in Fall Velocity Decreases when Plunger Passes Hole in Tubing

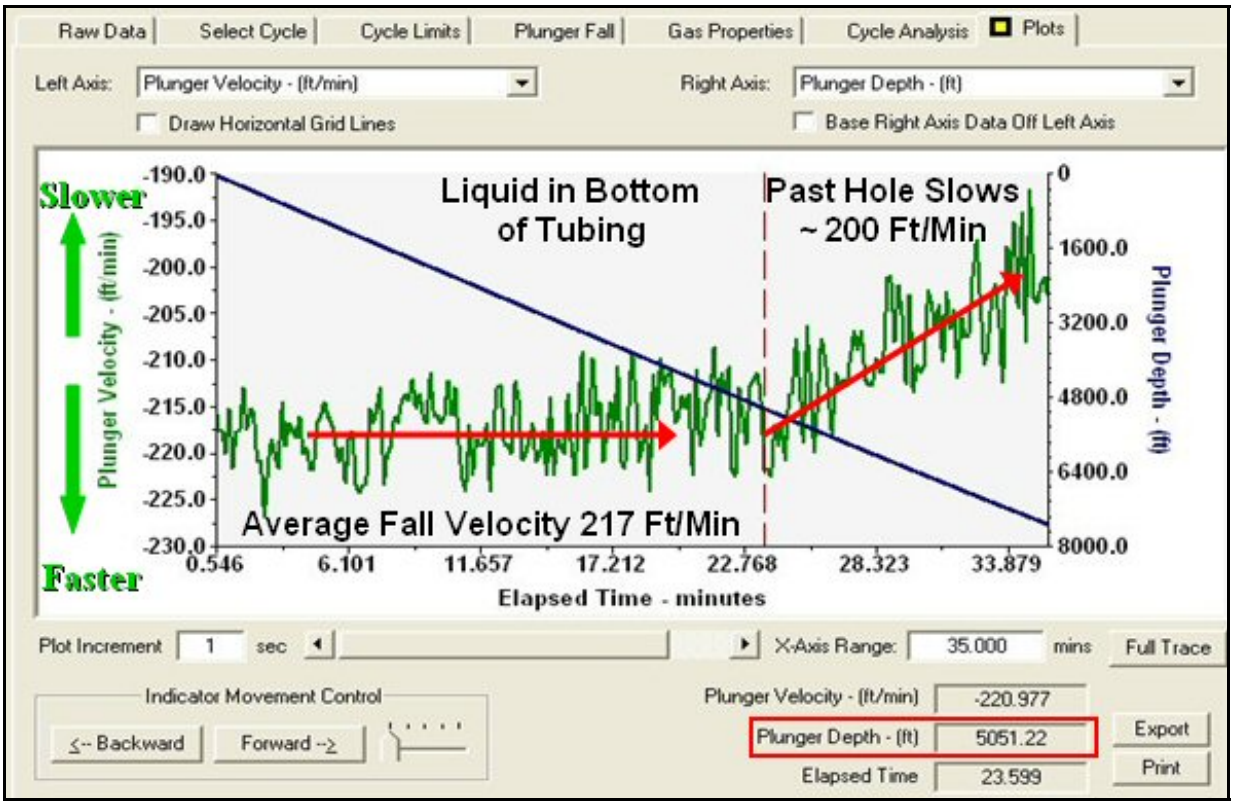

Figure 14 – Tubing Pressure Change Increases when Plunger Passes Hole in Tubing

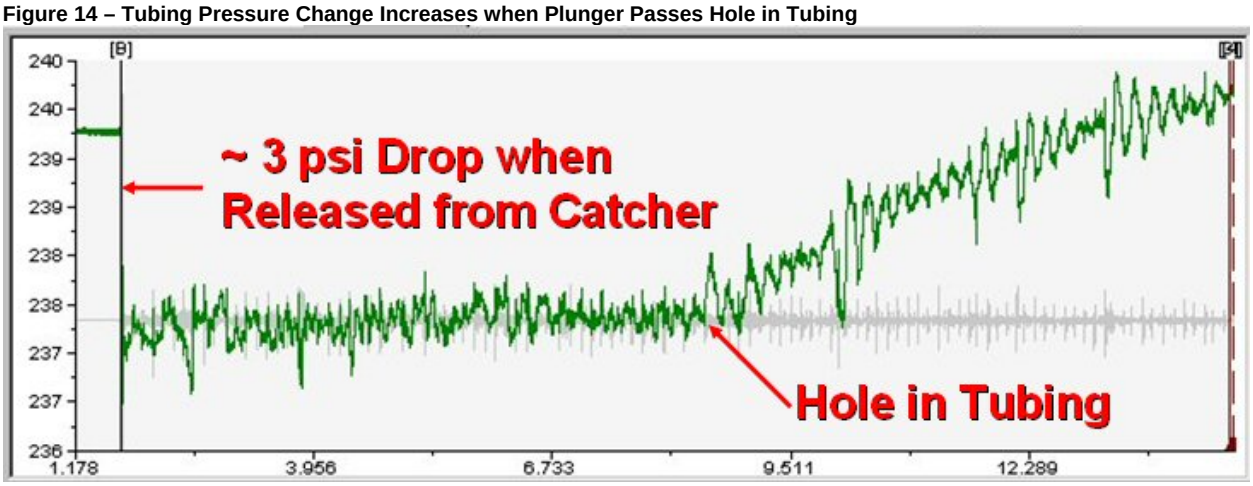

Figure 15 – Tubing Pressure Suddenly Increases when Plunger becomes Stuck on Tubing

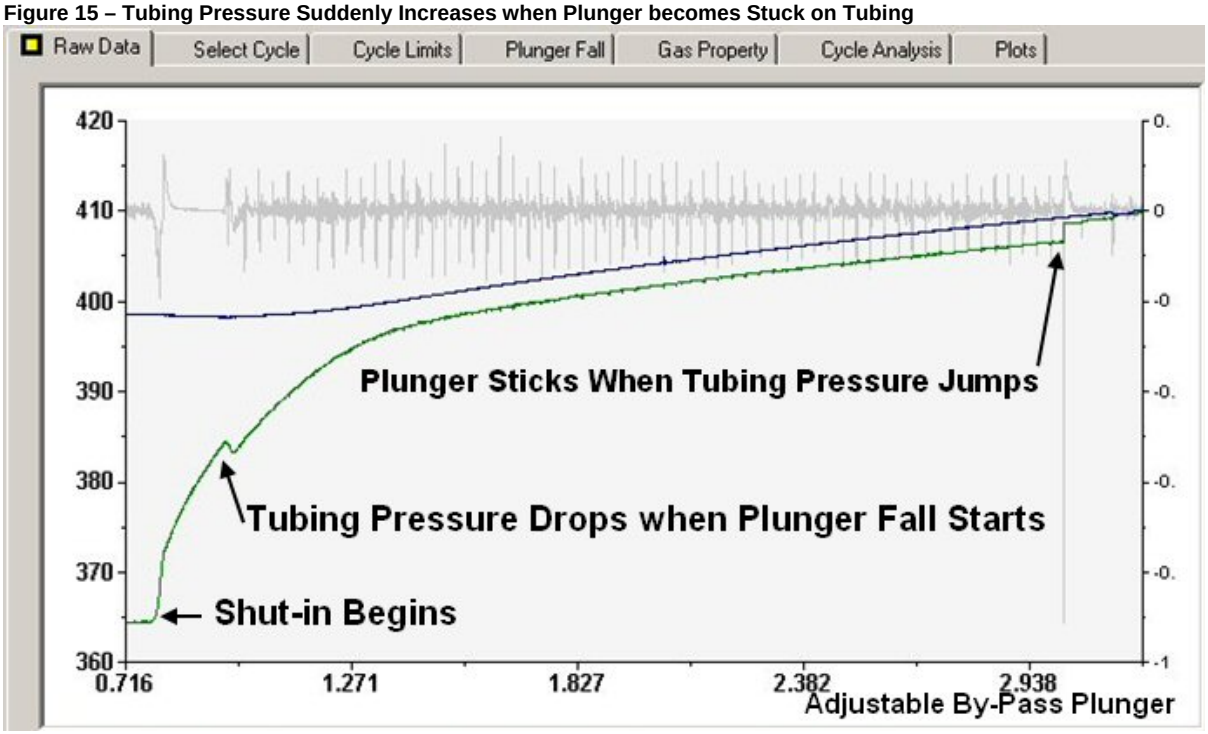

Figure 16 – Shut-in time Period too Long

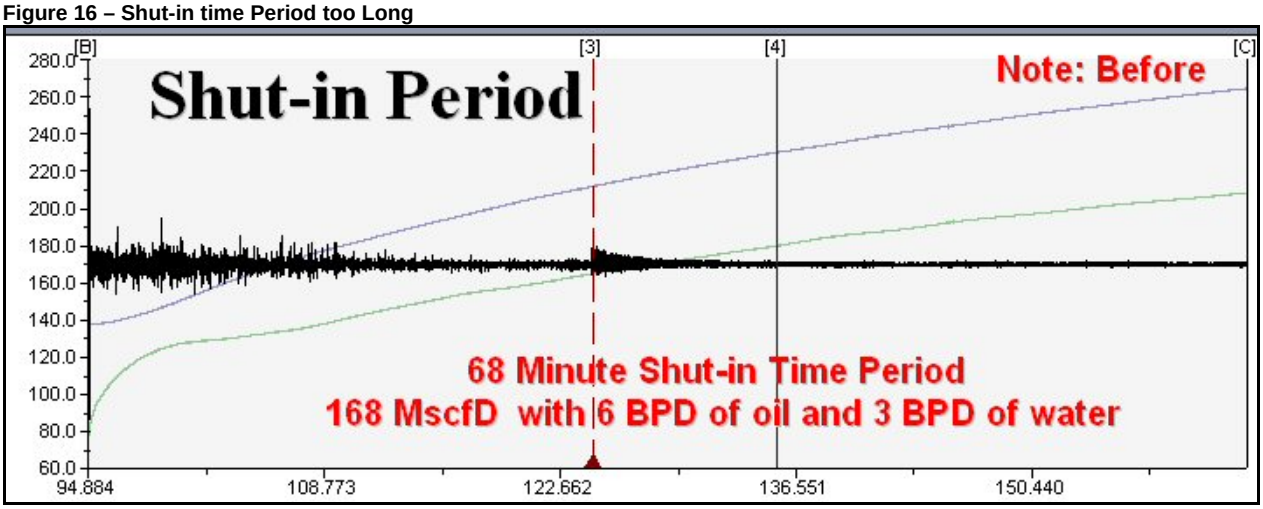
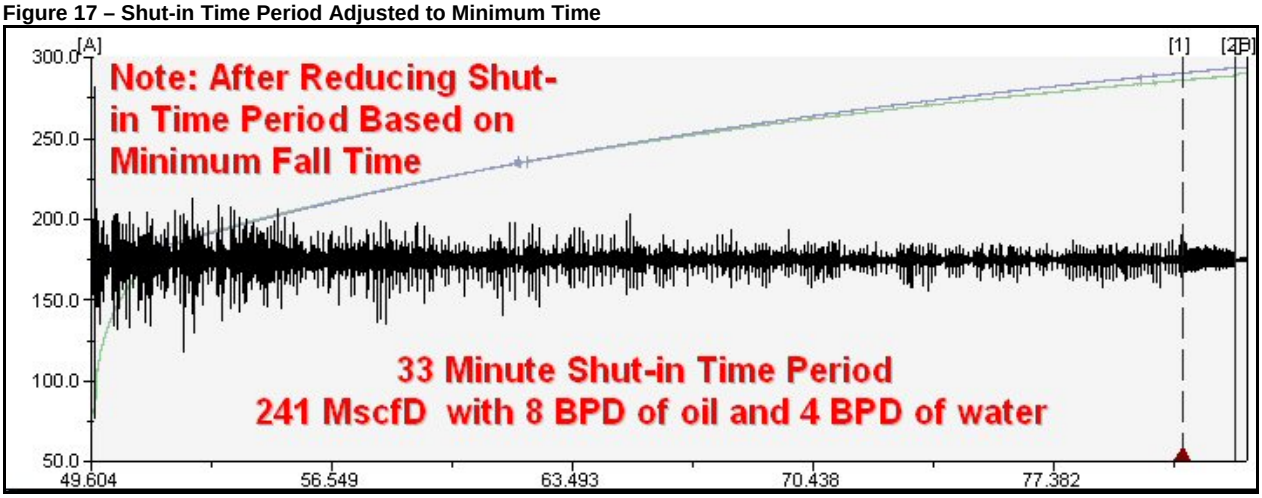
Figure 17 – Shut-in Time Period Adjusted to Minimum Time