SPE-164495-MS

Measured Plunger Fall Velocity Used to Calibrate New Fall Velocity Model

O.L. Rowlan, J. McCoy, Echometer Company; J. Lea, PLTech LLC; R. Nadkrynechny, C. Cepuch, T-RAM Canada Inc.

Copyright 2013, Society of Petroleum Engineers

This paper was prepared for presentation at the SPE Production and Operations Symposium held in Oklahoma City, Oklahoma, USA, 23−26 March 2013.

This paper was selected for presentation by an SPE program committee following review of information contained in an abstract submitted by the author(s). Contents of the paper have not been reviewed by the Society of Petroleum Engineers and are subject to correction by the author(s). The material does not necessarily reflect any position of the Society of Petroleum Engineers, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper without the written consent of the Society of Petroleum Engineers is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of SPE copyright.

Abstract

Plunger fall velocities for various plungers have been measured in many different wells in the field and measured in a large scale well simulator. A new theoretical plunger fall velocity model has been developed. This model equates plunger fall velocity to be inversely proportional to a constant multiplied by the square root of the density of the gas the plunger falls through. The measured fall velocity at a specific pressure and temperature is used to calibrate the model, and then the model can be used to calculate fall velocity at other conditions for the same plunger or used to show how changing a feature like plunger weight can impact fall velocity. The model's predicted fall velocity for different types of plungers will be compared with measured fall velocities.

A large scale plunger lift well simulator was used to determine plunger fall behavior in clear PVC tubing through compressed air and through gas free water. The performance of 36 different types and metallurgies of plungers were measured. Both in the field and at the well simulator an acoustic instrument was effectively used to accurately measure plunger fall velocity.

All plungers have the same general trend of fall velocity; where the plunger fall velocity is fast at low pressure and slows at higher pressure. Construction features of plungers and well conditions impacting plunger fall velocities will be highlighted. Using published fall velocities to determine the shut-in time period for a particular plunger type but may not be accurate for a well, because well pressure significantly impacts plunger fall velocity. The knowledge of how various parameters impact plunger fall velocity allows the operator to determine if the plunger has reached the bottom of the tubing by the end of the shut-in period and then optimize the plunger lifted well using the shortest possible shut-in time to maximize liquid and gas production.

Introduction

Conventional plunger lift is a low cost method for lifting liquids (water, condensate and/or oil) from gas and oil wells. This system reduces the cost of producing a well compared to other artificial lift methods, because stored formation pressure supplies the energy to lift the liquids. Lifting liquids from the well is achieved by closing a surface valve to store energy in the well during a shut-in time period and then followed by opening the surface valve for a time period so liquids are unloaded as gas flows to the surface. During shut-in the gas flow down the flowline is stopped when the controller closes the surface motor valve. The plunger leaves the lubricator to begin its fall from the surface due to a tubing pressure increase caused by closing the motor valve or when the plunger is released from a catcher. The plunger falls through gas until entering the accumulated liquid at the bottom of the tubing. The plunger then falls through the accumulated liquid at the bottom of the tubing. The shut-in time period should be sufficient length for the plunger falls to the bottom of the tubing and arrive at the bumper spring. During the shut-in time period the casing pressure should build to store sufficient energy to unload the accumulated fluids and the plunger to the surface when the motor valve opens. Once the plunger is on bottom and sufficient unloading energy is stored, then the controller opens the surface valve into the lower pressure flowline. High pressure gas in the tubing above the liquid column flows down the flow line and the high pressure gas in the casing begins to decrease by expanding to fill the tubing and displace the plunger and most of the liquid above the plunger to the surface. During unloading the plunger serves as an interface to prevent excessive energy loss, the energy loss is due to leakage of high pressure gas past the plunger or slippage of liquid back down the tubing. This plunger operation cycle is continually repeated in order to produce the well.

An operator can produce from the well efficiently if the plunger fall rate, plunger location, and time the plunger takes to fall

to the liquid and bottom of tubing are accurately known. The distance to the plunger and the rate of fall can be determined by examining the acoustic signal created by a falling plunger. A difference in pressure exists across the plunger as it falls depending upon the seal, weight and area of the plunger plus other factors. This difference in pressure above and below the plunger depends on the type of plunger and typically range from 1 to 4 psi. During the plunger fall when the plunger is in contact with the tubing collar recess a portion of the plunger weight is transferred off of the gas and onto the tubing, this sudden transfer of the differential pressure acting across the plunger generates an acoustic pulse (change in pressure). The acoustic pulse generated at the tubing collar recess, travels through the gas to the surface to be detected a microphone and the change in pressure can be detected by a tubing pressure transducer. These acoustic pulses are normally detected as a plunger falls down the relatively dry tubing interior above the gaseous liquid column at the bottom of the well. These acoustic pulses created in the tubing collar recess are monitored at the surface so that the plunger travel velocity and location are determined on a tubing collar-by-collar basis.

Plungers provide a type of pressure seal with the tubing; **Fig. 1** shows a 2.4 psi pressure drop at the beginning of shut-in tine period as the plunger leaves the lubricator, where the weight of the plunger is being applied to the tubing gas and depressing the pressure above the plunger. The 2.4 psi differential pressure is approximately equal to the plunger weight (8 lbs.) divided by the internal area of the 2.375 inch tubing. **Table 1** list the pressure applied to the gas by 36 different types of plungers, these pressure drops were measured during testing performed at the plunger lift well simulator. At the top of the table the heavy 13.3 lb triple pad plunger having a good seal applies a 3.8 psi pressure drop to the gas. At the bottom of the table the lightest 0.708 lb Venturi titanium 4.7mm plunger applies a 1.04 psi pressure drop to the gas. When the seal is sufficient between the tubing and the plunger moving relative to the gas then a pressure drop across the plunger is created. This pressure drop across the plunger results in an acoustic pulse being generated as the plunger falls past each tubing collar recess. During the plunger lift cycle a digital acoustic fluid level instrument can record output from a microphone attached to the tubing at the surface of the well, the falling plunger creates acoustic signals which are digitally recording as a function of time. This technique of passively monitoring the acoustic and tubing pressure signals does not require the periodic firing of the gas gun to determine the position of the plunger through echo ranging[1]. Processing the signal created by the plunger falling past each tubing collar recess, allows the depth and fall velocity of the falling plunger to be determined.

Fig. 2 is a plot of the casing pressure, tubing pressure and acoustic data acquired during one complete cycle of a typical plunger lift system. 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. The key events that occurred during the cycle are annotated on **Fig. 2**. **Table 2** list the casing pressure, tubing pressure and the time of each key event occurring during the 11.4 minute **Unloading**, the 22.1 minute **Afterflow** and the 67 minute **Shut-in** time periods of a cycle. For this cycle the dual padded plunger fell through 7309 feet of gas at an average fall velocity of 168.3 feet per minute and fell through 434 feet of gassy fluid at an average fall velocity of 38.9 feet per minute, reaching bottom in 57.0 minutes of elapsed time. The plot shows the data over the time period for one complete plunger cycle. The plunger was resting on bottom for 10 minutes and increased gas flow from the well is possible if the Shut-in time is reduced by up to 10 minutes. The plunger lift operation cycle had a time period of 100.5 minutes and repeated at a frequency of 14.3 cycles per day would be sufficient to remove the liquids that accumulate at the bottom of the tubing thus keeping the gas flowing at the desired rate.

When the plunger falls into the gaseous liquid column at the bottom of the tubing where the tubing pressure is above the 300-400 psig range, then the acoustic and pressure signals the plunger creates as plunger travels past tubing collar recesses in the gaseous liquid column can often be detected at the surface and fall velocity and plunger location can also be accurately determined when the plungers below in liquid level in the tubing. In general if the tubing pressure is too low when the plunger enters the gassy liquid column at the bottom of the tubing, then the acoustic pulses transmitted through the liquid are not usually detected by the surface transducers. But when the tubing pressure is sufficiently high, then it is a normal occurrence to see acoustic signal from the plunger passing the tubing collar recesses below the gaseous liquid column. **Fig. 3** display of collar signals from dual pad plunger falling at 201 feet per minute through gas and then falling at 38 feet per minute through the gassy liquid column. The time when the plunger enters the gaseous liquid is usually easy to identify, because the acoustic signal suddenly changes and the consistently spaced echoes from the tubing collars recess are not present. In some cases the acoustic noise level drops, indicating that the signal from the submerged plunger is not being transmitted out of the liquid through the gas to the surface. In other cases the signal gets noisier because the plunger had been blocking the noise of the gas flow breaking out of the liquid. When the plunger finally rests on bottom on the bumper spring the noise level may drop again; in some of the field tests a 0.4 psi pressure increase is seen when the plunger weight is transferred onto the bumper spring at the bottom and the plunger weigh is no longer depressing the tubing pressure. Identifying this unique signal allows the operator to determine the precise time when the plunger reached bottom after the plunger submerged into the gaseous liquid column.

By accurately measuring the plunger fall velocity, the proper shut-in time for the plunger lift installation can be determined. The knowledge of how various parameters impact plunger fall velocity allows the operator to ensure that the plunger has

reached the bottom of the tubing by the end of the shut-in period. Setting the well's controller to have the shortest possible shut-in time can maximize condensate and gas production from the plunger lift well.

How Fall Velocity is Determined

Fig. 4 displays the technique used to determine the plunger fall velocity as each consecutive tubing collar echo is identified. Plunger fall velocity is calculated using **Eq. 1**.

Velocity = (Di - Di-1) / (Ti - Ti-1) …….. (1)

The acoustic trace at the top of **Fig. 4** displays the location of tubing collar echoes 21 through 27. The times, depths and calculated velocities are displayed in the table at the lower right corner of the figure. As the time to each tubing collar is identified, the depth is incremented by the average joint length for the well. For example the fall velocity for collar 22 is determined by using the elapsed time between collar echoes from the time when the plunger fell past collar 21 (labeled C21 at Ti-1= 5.663 minutes) and the time when the plunger reached the tubing collar 22 (labeled C22 at Ti = 5.802 minutes). Using the change in depth to be equal to the average joint length of 32.2 feet/joint; the calculated fall velocity of the plunger was -230.9 ft/min for collar 22 at a depth (Di) of 708.4 feet. (Negative sign on the plunger fall velocity indicates the plunger is falling down) **Fig. 5** shows the plunger fall velocity decreasing smoothly as a function of time. Although there seems to be some scatter of velocities on the plunger velocity trace, note that the left vertical scale is amplified and that the general trend of the velocity is to consistently decrease as time (plunger depth) increases. Significant deviations from the trend of the plunger gradually slowing with respect to depth could indicate a well problem or could be an indication that the identification of the collar signals should be reviewed and verified.

Theoretical General Plunger Fall Velocity Model

A new theoretical general plunger fall velocity model has been developed that can be used to predict plunger fall velocity in a well at any pressure and temperature condition. If the fall velocity for a particular plunger is measured in a well at a specific pressure and temperature, then the general model is used to determine the calibration constant, C. Using a measured fall velocity at a known pressure and temperature to calibrate the general model, allows the general plunger fall velocity model to be used to calculate the plunger fall velocity at other pressures and temperatures.

Two different equations were considered to be representative of the conditions that control the plunger fall through the gas in the tubing. The "drag model"[2] is where plunger acts as an object falling through the gas where the fall velocity is controlled by the drag force of the gas acting on the plunger.

Drag Model: $$\mathrm{Cd}\rho \mathrm{AV}^2/(2gc) = \mathrm{Wt} \quad \text{..... (2)}$$

For the Drag Model the plunger weight is set equal to the drag force acting of the plunger. At a pressure, temperature and gas gravity the density of the gas is determined. **Eq. 2** models a constant mass of gas moving past the plunger, where the kinetic energy on the plunger changes to keep the passage of gas constant. The "orifice model" is where the plunger/tubing seal act as a choke allowing a specific amount of gas to be pushed past the plunger as the plunger falls through the gas in the tubing.

Orifice Model: $$(\mathrm{CdAnn})\sqrt{(2\mathrm{Wt\ gc}/(\mathrm{A}\ \rho))} = \mathrm{V\ A} \quad \text{.. (3)}$$

For the Orifice Model gas is flowing from below the plunger to above the plunger through the area providing the seal between the plunger and the tubing. At a pressure, temperature and gas gravity the density of the gas is determined. **Eq. 3** calculates gas flowing through the plunger/tubing annular area. For a specific plunger in the tubing there is differential pressure acting on the gas, the term Cd x Ann is used to determine the differential pressure required to support the plunger weight as the plunger falls through the gas. In this model the plunger acts a choke where the differential pressure across the plunger provides the support at a specific velocity and gas density. The generalized plunger fall model can be derived by rearranging the terms in either **Eq. 2** or **Eq. 3**.

General Plunger Fall Model: $$V = \mathrm{C}/\sqrt{\rho} \quad \text{.....(4)}$$

The General Plunger Fall Model, **Eq. 4**, equates plunger fall velocity to be inversely proportional to a constant multiplied by the square root of the density of the gas the plunger falls through. A measured fall velocity at a specific pressure and temperature is used to determine the constant C. Once the constant C is determined, then the General Plunger Fall Model can be used to calculate fall velocity at other conditions. **Fig. 6** compares the Drag Model to the Orifice Model to show that when a plunger's measured fall velocity at a specific pressure and temperature is used to calibrate the model, then both equations simplify to the same curve (General Plunger Fall Model). The Orifice or Drag model can also be calibrated to a specific plunger and used to show how changing a feature like plunger weight can impact fall velocity. From field measurements it has been observed that all plungers fall slower at higher pressure and faster at lower pressure. During shut-

in the gas that flows into tubing increasing the tubing pressure and increasing the density of the fluids in the tubing, field observations confirm the general model predictions of the plunger fall velocity slowing inversely proportional to the square root of the density of the gas the plunger is falling through.

Plunger Fall Velocity Function of Gas or Fluid Density

Fig. 7 displays the tubing pressure during the shut-in time period and plunger fall velocity for a dual pad plunger lifted well. The tubing pressure and the density of the gas are increasing during the shut-in time period as gas accumulates in the tubing. In this well there is liquid in the bottom of the tubing and there is no hole in the tubing. The tubing is not grooved or worn. When these conditions occur in a plunger lifted well the plunger begins falling with a faster velocity and gradually slows down as the plunger gets deeper into the tubing. The data from field testing usually shows the plunger fall velocity decreases as the plunger get closer to the bottom of the tubing. The behavior of the plunger slowing down as it falls deeper in the well agrees with the General Plunger Fall Model since the increasing pressure is increasing the gas density inside the tubing.

Fig. 8 shows the measured fall velocity for the same dual pad plunger in the same 2.375 inch tubing string in the same gas well for five (5) consecutive shut-in time periods. Gas flow into the wellbore from the damaged formation was severely restricted, so for each cycle the well pressure decreased because the gas inflow did not replace the gas used to unload the well. The average tubing pressure for the 5 different tests was lower for each test and the pressure decreased from 177.7 psia for cycle 1, to 145.4 psia for cycle 2, to 116.7 psia for cycle 3, to 88.8 psia for cycle 4, and to 56.3 psia for cycle 5. For this padded plunger there is an almost linear 1.75 ft/min increase in the fall velocity per each 1 psi drop in tubing pressure. **Fig. 9** shows the predicted fall velocity using the General Plunger Fall Model for the dual pad plunger calibrated to the measured fall velocity of 394.8 ft/min at a pressure of 88 psia. There was an average absolute error of 16.3 psi when comparing the predicted fall velocity from the General Model to the measured fall velocity in the well. For this example the decreasing density of the gas had the primary impact on the plunger fall velocity. In this case the dual padded plunger fell down the tubing at 478 ft/min at 56.3 psia average tubing pressure, but fell at what is considered a normal 256 ft/min fall velocity for a dual pad plunger when the tubing pressure was 177.7 psia. When the pressure is low the plunger fall velocity is much faster than what is considered normal, but when the pressure is higher the plunger fall velocity would be at a rate that is considered normal.

Fig. 10 shows the plunger fall velocity for solid cleanout type of plungers measured in 40 different wells versus tubing pressure. The predicted cleanout plunger fall velocity curve was calculated using 300 ft/min and 261.7 psia as input into the General Model. Comparing the predicted fall velocity to the measured fall velocity there is an average error of 1.3 ft/min and an absolute error of 40.1 ft/min. In this set of data most of the measured plunger fall velocities were over pressure ranges from 100 to 440 psia. The General Model predicted fall velocity at the highest pressure of 815 psia matched the 165 ft/min measured in one of the wells. The General Model predicted fall velocity at the lowest pressure of 17.5 psia within 100 ft/min of the 1325 ft/min measured in the laboratory at the large scale plunger lift well simulator. The General Model accurately predicted the fall velocity to closely match measured fall velocities from 0 to 800 psig for the solid cleanout type of plunger.

Slow fall velocities due to high pressure also have an impact on plungers that are considered to fall fast such as the dual pad bypass type of plunger. Previously published[3,4] information stated that the dual pad bypass type of plungers had fall velocities that were greater than 1000 ft/min. **Fig. 11** displays the measured fall velocity for a new dual pad bypass type of plunger in 2.375 inch having tubing pressures during shut-in ranging from 1732 to 2213 psig. In this well the 2 hour and 30 minute shut-in time period was not a long enough for the dual pad bypass type of plunger to fall to the bottom. During shut-in the average fall velocity of 78.4 ft/min allowed to plunger to hit liquid at a depth of 9437.4 feet from the surface. There was 891.6 ft of “gassy” liquid above the end of the tubing at the depth of 10329 feet. With the high well pressure the signal from the plunger falling past the tubing collars in the gassy liquid column could be identified and the plunger fell at an average 22.8 ft/min. With a 22.8 ft/min fall velocity the elapsed time would require 39.1 minutes to fall through the gaseous liquid column. Total shut-in time would have required 160.3 minutes for the plunger to fall through the gas and to fall through the gassy fluid. The controller’s shut-in time was set to be 150 minutes; under these conditions the controller opened too early to completely unload the well because the plunger was likely 228 feet off the bottom. The high pressure and corresponding slow fall velocity resulted in leaving liquid in the well and not effectively unloading the well, because the fall velocity for the dual pad bypass type of plunger was much slower than expected at these high pressures.

In general the fall velocity through gassy fluid is approximately 40 ft/min. But, when a well is treated with surfactant the gassy fluid is less dense and the plunger fall velocity is near 80 ft/min. When a plunger lifted well is treated with surfactant the gaseous liquid column may stand 3 times taller than a normal untreated gaseous liquid column for the same differential tubing and casing pressure. The plunger falls about 2 times faster and the height of the surfactant treated gaseous liquid column is approximately 3 times higher, when a plunger lifted well is treated with surfactant additional shut-in time may be required to allow time for the plunger to fall to bottom.

Deviation

When the wellbore is deviated the fall velocity of the plunger would be expected to decrease as friction increased with the increasing well bore deviation. **Fig. 12** shows that the solid type of plungers slows down due to increased friction when the well bore becomes deviated. In this horizontal well the solid type cleanout type of plunger slowed from a 344 ft/min fall velocity to a 280 ft/min after going past the kick off point in the well. **Fig. 13** shows a padded type of plungers increase in speed after going past the kickoff point in a horizontal well because the seal between the plunger and tubing is lost when weight of the plunger compresses the springs in the pads due to gravity. The dual padded plunger velocity increased from the "normal" 230 ft/min fall velocity to 450 ft/min after entering the deviation, in this example the increased friction appears to have little impact on fall velocity where the collapse of the springs and the loss of the seal had a major influence on the fall velocity. **Fig. 14** displays the fall velocity for a padded plunger in an S-shaped deviated wellbore; in this type of well the well is initially vertical, then kicks off to some deviation angle and when the offset is achieved then kicks back to vertical. **Fig. 14** shows the pads collapse near 20 degrees of deviation from the vertical and once the well becomes near vertical the pads re-seal and the plunger slows back to the normal fall velocity for a padded plunger. Wellbore deviation above 20 degrees results in padded plungers increasing in fall velocity due to loss in seal, while the solid types of plungers tend to slow down in fall velocity due to increased friction.

Gas Flow

Fig. 15 shows the tubing pressure, instantaneous gas flow rate, and the plunger fall velocity where a standing valve is opening and closing during the shut-in period, while the plunger is falling through the gas in the tubing. When the well pressure outside the tubing increases by 4 psi the standing valve opens allowing gas to enter the tubing for approximately 2 minutes of time at a gas rate up to 40 MscfD. When the standing valve is open the increased gas rate causes the plunger to slow from approximately 380 ft/min to a more typical 200 ft/min fall velocity. When there is no gas inflow into the tubing the standing valve closes and the plunger falls faster than normal. When gas flows into the tubing, then the increased gas flow rate slows the plunger fall.

Sticking of the Plunger

As plungers falls through the gas in the tubing the weight of the plunger depresses the tubing pressure above the plunger. This pressure drop can be seen in **Fig. 16** when the plunger became stuck while falling down the tubing during the shut-in period. Immediately when the plunger became stuck and stopped, the tubing pressure suddenly increased by approximately 3 psi and when the plunger began to fall again the tubing pressure decreased by an equal 3 psi amount. If the plunger becomes stuck in the tubing all that may be required to unstuck the plunger is a fluid level shot down the tubing, the pressure wave from the gas gun discharged at the surface travels down the tubing and often will exert sufficient force to push and free a stuck plunger. When the pressure wave generated by a gas gun hits the plunger the force exerted is usually sufficient to un-stick the plunger and to cause the plunger to resume falling down the tubing. **Fig. 17** shows a plunger falling down the tubing where chemical is being injected down the tubing to treat for corrosion. The padded plunger starts falling at a normal velocity, but after just 5 minutes of elapsed time the plunger slows to a fall velocity near 100 ft/min. For approximately 1 minute the plunger increases in speed, but again slows down to near 50 ft/min. After 25 minutes of elapsed time the plunger had fallen to a depth of 1937 feet from the surface of the well. The plunger lift system is operating under timer control after 25 minutes of elapsed time the end of the shut-in time period should have been reached and the motor valve opens to unload the well. Data was acquired on this well because to plunger was coming to the surface dry and the plunger was having high energy impacts on the lubricator, because of the high velocity arrivals the operator was concerned about potential damage to the surface equipment on this well. Troubleshooting this problem was a simple process during 25 minutes of data acquisition by determining that the plunger was falling slowly down the tubing because the chemical treatment into the tubing was creating a sticking problem. When the plunger gets stuck and does not fall to bottom, damage to the surface equipment is possible, dangerous conditions can be avoided when these type of problems are identified.

What Has Been Published Previously Concerning Plunger Fall Velocity

During the time period of 2000-2003 plunger fall studies[3] were conducted on many different plunger lifted wells and it was determined that the plunger manufacture features have an effect on plunger fall velocity. The various construction features of different types of plunger's impact fall velocity. Some of these features are: diameter, effectiveness of seal, increased friction due to contact with the tubing, if the plunger falls straight or spins, and the age of plunger or amount of wear. Some construction features cause a plunger to fall rapidly through the tubing, while other features cause the plunger to have a slow fall velocity.

As the diameter of the plunger increases, the fall velocity of the same type plunger decreases. As the diameter of a plunger increases, then the weight of the plunger increases. Friction between the plunger and tubing increase as the diameter increases, because the increase in diameter causes a larger surface area of the plunger to contact the tubing. The cross-sectional area of the plunger increases by the square of the diameter and less differential pressure is required to resist the fall of the plunger. The larger diameter plunger increases the friction and the larger area increases the force due to differential

pressure applied to the plunger cross-sectional area, which result in slower fall speed. The presence of pads on a plunger results in slower fall velocities when compared to solid plungers of the same diameter. The slower fall velocity of the pad plunger is due to the better seal and the additional friction between the tubing and plunger caused by the springs behind the pads that force the pads against the tubing wall.

The effectiveness of the seal to prevent or allow fluids to flow past the plunger has a major impact on fall velocity. Padded plungers have the best seal and have a slow fall velocity. If rubber or neoprene is placed between a set of pads and the plunger body, then the improved seal results in a much slower plunger fall. This better seal feature might be desired if liquid or gas slipping past the plunger is a problem. Rubber or neoprene provides a good seal to restrict gas from flowing past the plunger and results in the slowest fall velocity for padded types of plungers. The by-pass type of plunger has a valve that opens to reduce restriction of gas flow past the plunger. The by-pass creates a large opening through the plunger and this large opening allows fluids to flow with less restriction past the plunger. The ability to by-pass fluids through the plunger results in the higher fall velocity.

The brush plungers have the largest difference in fall velocity for any type of plunger. The fall velocity of the worn brush plunger ranged from a high speed of 477 ft/min down to the slowest speed of 150 ft/min of a new brush. A new brush with soft bristles that fill the area between the plunger and tubing will result in a very slow falling and efficient plunger. Other new brush plungers have stiff nylon bristles that do not contact the tubing wall, this type of brush plungers fall much faster due to having a poorer seal. A worn out brush that appears to be smooth and shiny due to paraffin clogging the bristles and worn bristles that do not contact the tubing can fall very fast. Throughout the life of a brush plunger, the fall velocity of the plunger increases as the brush bristles wear off due to abrasion with the tubing wall.

In all cases when new plungers fall velocities were compared to the existing plunger in the same well, the older worn plungers fell faster. Generally, as the plunger wears out due to age, then the fall velocity increases. Gas slippage increases as the plunger becomes worn and the seal less efficient; if a worn plunger is replace then the resulting increase in gas production can quickly pay off the cost of the new plunger.

Solid type of plungers that have spiral groves at the top and bottom of the plunger tend to spin the plunger at it falls during the shut-in time period. The spinning motion of the plunger resulted in slower fall velocities when compared to a solid grooved plunger of the same diameter.

Summary

Density of the fluids in the well have the most significant impact on plunger fall velocity; gas density can impact plunger fall velocity more than specific manufacture features used in the construction of a plunger. There is not a normal fall velocity for a particular type of plunger, since the density of the gas due to pressure has such a large impact. For a particular field where line pressures are similar from well to well, then similar types of plungers will have similar fall velocities. But where pressures are different, then the density of the tubing gas and fluid have a significant impact on plunger fall velocity thereby making the plunger fall velocity unique to the specific conditions in a well. Determining what factors impact plunger fall is a valuable technique for use in the diagnosis of problems encountered in operating a plunger lifted well. Adverse conditions can be identified and the fall velocity of the plunger can be determined. Following is currently known concerning plunger fall velocity:

1. Diameter of Plunger – Larger Diameter Falls Slower
2. Effectiveness of Seal between Plunger and Tubing – Better Sealing Plunger Falls Slower
3. Brush stiffness – If the Bristles do not provide an effective seal then the plunger falls faster
4. Increased friction due to contact with the tubing – Plunger Falls Slower
5. Old age/increased wear – as the plunger wears the seal is poorer and the worn plunger falls faster
6. If Gas can pass through plunger (i.e. Bypass) – then a plunger falls faster
7. When the plunger becomes stuck – a corresponding pressure increase due to plunger weight transfer is seen
8. If the Tubing is Sticky – the plunger falls slower
9. Wellbore Deviation – more than 20 degrees of deviation impacts plunger fall velocity
    a. Padded Plungers Fall Faster due to collapse of springs and loss of seal
    b. Solid Plungers Fall Slower due to Increased Friction
10. Gas Flow Rate Into The Tubing – gas flow into tubing reduced plunger fall velocity
11. Density of Gas controlled by Pressure and Temperature
    a. High Pressure and plunger fall is Slow
    b. Low Pressure and plunger fall is Fast
12. Liquids increase density – plunger falls slow
    a. Surfactant lightens gradient and plunger falls faster, but more time may be required
    b. High pressure also causes plunger to fall more slowly through liquid

Large Scale Plunger Lift Well Simulator

During the summer of 2011 a large scale plunger lift well simulator was constructed at the T-RAM facility in Grande Prairie, AB Canada. The simulator was constructed using clear schedule 40 NSF 2.375 inch PVC pipe having an internal dimension of 2.047 inch. The 25 ft vertical PVC tubing section tubing was supplied with compressed air at the bottom from a 200 psi large volume air compressor. The plunger lift well simulator was used to study plunger fall behavior in compressed air and in gas free water. Each test was recorded with video and all differential pressure measurements were acquired at 30 samples per second.

Plunger fall through air test was designed with the intent of determining the minimum flow rates required to lift and float each plunger in a dry well. Air flowed through the simulator at a constant measured controlled rate with sufficient pressure to lift and float each plunger to heights of .5m, 1.75m and 3m. The process of floating each plunger at 3 different heights in the tubing was repeated 3 times and the acquired data showed there was almost no difference in pressure or the measured flow rate required to hold a plunger at the specified heights/distances from the bottom of the simulator. Air flow rates were measured using a flow meter tapped into the inlet of air flow before entering the vertical section of the simulator. The air flow rate was converted into velocity at the float pressure, the gas velocity past the plunger was assumed to be equal to the fall velocity of the plunger through air. The results of the 36 different types and metallurgies of plungers fall through air are displayed in **Table 1**.

Plunger fall through water test was designed to determine the fall velocity of various plungers through a gas free constant water column height. Each plunger was dropped into a liquid column and the time required to reach the bottom was recorded. **Fig. 18** shows the triple pad plunger to fell through 8.2 ft height of gas free water in 13.93 seconds for a fall velocity of 35.3 ft/min. The recorded data shows the pressure increase at the moment the plunger hit the water and drops the moment the plunger hit bottom. The time required for each plunger to fall through water can be precisely determined by identifying moment the pressure changes when the plunger hits the water and the moment the pressure changes when the plunger hits bottom. The results of the 25 different types and metallurgies of plungers fall through gas free water are displayed in **Table 3.**

Conclusions

A new theoretical general plunger fall velocity model has been developed. This model equates plunger fall velocity to be inversely proportional to a constant multiplied by the square root of the density of the gas the plunger falls through. The predicted fall velocity calculated using the general fall velocity has been confirmed by both laboratory testing and field measurements collected at many different wells. In previous technical papers plunger fall velocities have been published for specific types of plungers, but these fall velocities were only correct at the specific pressure and temperature conditions in the individual wells. Once the fall velocity for a particular plunger at a specific pressure and temperature is known, then the general model can be used to predict the fall velocities at other pressures and temperatures. When a plunger operational cycle is optimized[5,6], the change to the plunger cycle impacts the operating pressure and the new model should be used to determine the new fall velocity and corresponding shut-in time.

Determining the plunger fall velocity will allow the operator to set the minimum shut-in time for the plunger lift installation. Knowing the plunger fall velocity for specific well conditions will ensure that the plunger will reach the bottom of the tubing by the end of the shut-in period. Use of an acoustic instrument is an effective method to determine the fall velocity during the shut-in time period, plus provide a calibration point to input into the general fall model. Maximum production from the plunger lift installation will be obtained by having the shortest possible shut-in time equal to the time required for the plunger to reach bottom (as long as sufficient casing pressure exist to return the plunger and accumulated liquid to the surface). When using published plunger fall velocities to calculate minimum shut-in time, the operator should be aware that published fall velocities for a specific type of plunger can be used, but the fall velocity is only accurate for a specific pressure and temperature condition and may not be accurate at other well conditions.

Nomenclature

A = cross-sectional area of tubing
Ann = cross-sectional flow area between plunger and internal diameter of tubing
g_c = gravitational constant
ρ = fluid density
C_d = drag coefficient
C = General Plunger Fall Model Calibration Constant
V = plunger fall velocity
W_t = plunger weight

References:

1. Rowlan, O.L., McCoy, J.N. and Podio, A.L.: "Acoustic Liquid-Level Determination of Liquid Loading in Gas Wells," paper SPE 100663 presented at the 2006 SPE Western Regional Meeting, Anchorage, AK (May 8-10, 2006).
2. Divyakumar, G., Lea, J. F., Cox, J. and Oetama, T., "New Considerations for Modeling Plunger Performance", SPE 93997, for presentation at the 2005 SPE Production and Operations Symposium held in Oklahoma City, OK, U.S.A., 17 – 19 April 2005
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 OKC,, OK, U.S.A., 23–25 March 2003.
4. Rowlan, O.L., McCoy, J.N., and Podio, A.L, " Analyzing and Troubleshooting Plunger-Lifted Wells" SPE 102336, at the 2006 SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, U.S.A., 24–27 September 2006
5. Lea, J F, Rowlan, O. L., and McCoy, J. N., "Measurement and Calculation of Key Events During the Plunger Lift Cycle", SPE 110829, for presentation at the 2007 SPE Annual Technical Conference and Exhibition held in Anaheim, California, U.S.A., 11–14 November 2007
6. Rowlan, O.L., Lea, J. F., and McCoy, J.N., " Modified Foss and Gaul Model Accurately Predicts Plunger Rise Velocity" SPE 120636, at the 2009 SPE Production and Operations Symposium held in Oklahoma City, Oklahoma, USA, 4–8 April 2009
7. Baldwin, Z., Williams Companies " Pad Plunger in Highly Deviated Well #1" ALRDC Gas Well Deliquification Conference, Plunger Lift Seminar, Denver, CO February 22-24, 2010

Table 1 – Pressure Plunger Applies to Gas

	Plunger Type	Average Gas Rate MscfD	Pressure Plunger Applies to Gas Psi	Gas Velocity Past Plunger Ft/Min
1	Triple Pad	42.5	3.80	1075
2	Solid Cone Plunger	72.9	3.06	1919
3	Cleanout Wide Ring	65.2	2.91	1732
4	Dual Pad Style #1	42.3	2.83	1130
5	Dual Pad Style #3	41.1	2.75	1101
6	Solid Round Plunger	57.3	2.70	1541
7	Dual Pad Style #2	43.3	2.67	1167
8	Cleanout steel w/o holes	50.0	2.59	1352
10	Brush	37.0	2.43	1012
11	Wedge	53.9	2.38	1476
12	Solid Spiral	62.6	2.35	1719
13	Single Pad	50.5	2.26	1394
14	Cleanout Steel	49.9	2.24	1377
15	Sliding Sleeve	70.8	2.24	1956
16	Single Pad Stiff Spring	42.2	2.23	1165
17	Venturi Bypass Steel	72.1	1.95	2026
18	Mini Cleanout Steel	51.5	1.83	1458
19	Venturi Long 4.7mm	47.5	1.83	1345
20	Venturi Cleanout 4.7mm Steel	61.7	1.80	1749
21	Venturi Long 8.0mm	58.8	1.77	1670
22	Venturi Long 10mm	69.4	1.74	1975
23	Worn Venturi 1.73"	119.0	1.69	3397
24	Venturi Long Plug	41.4	1.68	1182
25	Venturi Steel 10mm	74.2	1.53	2138
26	Venturi Steel 8.0mm	65.0	1.49	1878
27	Venturi Steel 4.7mm	60.3	1.46	1745
28	Venturi Bypass Titanium	59.7	1.45	1729
29	Venturi Steel Plug	46.8	1.43	1358
30	Mini Bypass	61.4	1.41	1783
31	Worn Venturi 1.86"	66.7	1.41	1937
32	Venturi Cleanout 4.7mm Titanium	49.9	1.31	1460
33	Venturi Titanium 10mm	64.8	1.21	1905
34	Venturi Titanium Plug	42.5	1.17	1253
35	Venturi Titanium 8.0mm	55.0	1.16	1623
36	Venturi Titanium 4.7mm	47.6	1.04	1415

Table 2 – Casing Pressure, Tubing Pressure, and Time of Key Events Occurring During a Typical Plunger Cycle

Plunger Cycle Events	Elapsed Time Minutes	Tubing Pressure psi (g)	Casing Pressure psi (g)
[A] Valve Closes (Shut In Begins)	2.267	137.0	192.7
[1] Plunger Hits Liquid	47.467	235.5	273.1
[2] Plunger On Bottom	59.283	235.5	290.7
[B] Valve Opens (Unloading Begins)	69.267	272.8	306.0
[3] Liquid Arrives	79.550	126.3	235.1
[4] Plunger Arrives	80.717	206.2	231.5
[C] Valve Closes (Shut In Begins)	91.333	126.2	171.4

Table 3 – Plunger Fall through Gas Free Water

Seq #	Plunger Type	Elspased Time Seconds	Fall Velocity ft/min	Plunger Weight Lbs
1	Triple Pad	13.92	35.35	13.29
2	Brush	13.08	37.62	8.11
3	Venturi Long Plug	12.84	38.33	5.17
4	Dual Pad Style #1	12.30	40.01	7.26
5	Single Pad Dura Seal	11.88	41.42	6.42
6	Venturi Titanium Plug	10.74	45.82	0.71
7	Single Pad	10.20	48.25	6.81
8	Venturi Titanium 4.7mm	9.60	51.26	0.71
9	Venturi Steel Plug	9.30	52.92	1.90
10	Venturi Clanout 4.7mm Titanium	9.12	53.96	1.11
11	Venturi Long 4.7mm	9.12	53.96	5.17
12	Cleanout Steel	8.52	57.76	7.12
13	Venturi Wedge	8.10	60.76	7.49
14	Venturi Steel 4.7mm	8.04	61.21	1.90
15	Venturi Titanium 8.0mm	7.92	62.14	0.71
16	Mini Cleanout Steel	7.92	62.14	5.98
17	Venturi Long 8.0mm	7.44	66.15	5.17
18	Venturi Cleanout 4.7mm Steel	6.96	70.71	2.82
19	Venturi Titanium 10mm	6.72	73.23	0.71
20	Venturi Steel 8.0mm	6.60	74.56	1.90
21	Venturi Long 10mm	6.12	80.41	5.17
22	Sliding Sleeve	5.70	86.34	6.54
23	Venturi Steel 10mm	5.64	87.26	1.90
24	Venturi Bypass Titanium	3.24	151.89	1.78
25	Venturi Bypass Steel	2.70	182.67	3.13

Figure 1 – Pressure Drop Due to Plunger's Weight Pushing on Tubing Gas at Beginning of Shut-in

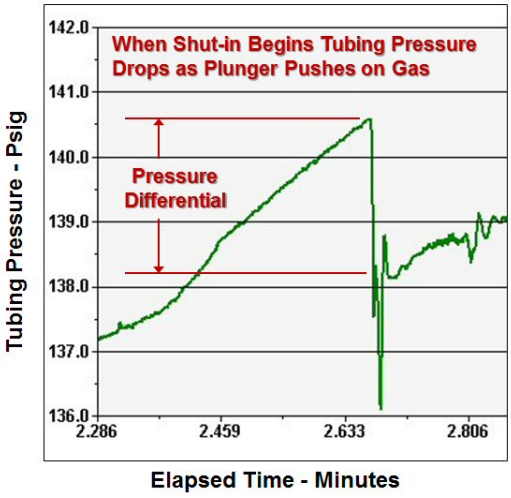


Figure 2 – Typical Plunger Cycle Record of High Speed Acoustic, Tubing & Casing Pressure

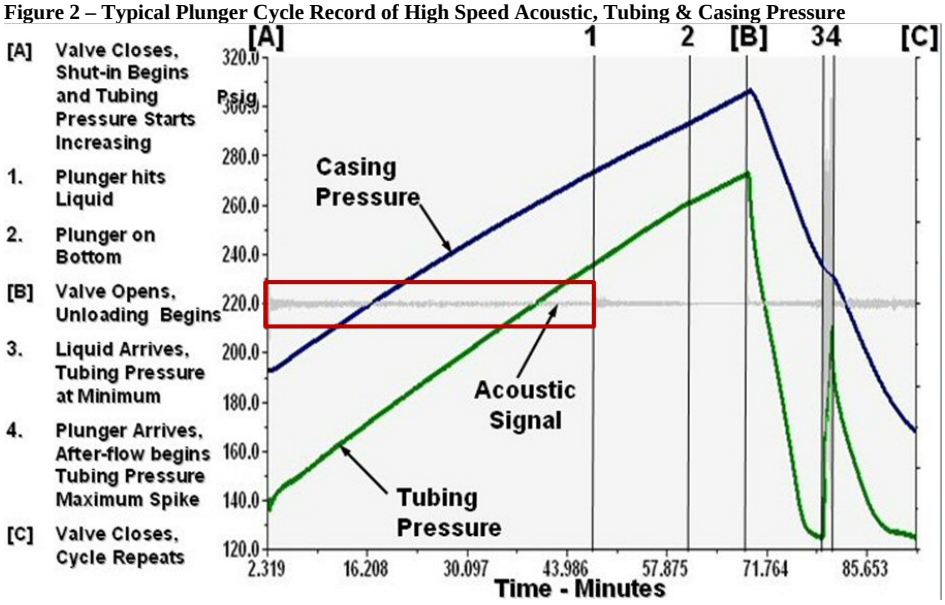


Figure 3 – Display of Collar Signals from Dual Pad Plunger Falling Through Both Gas and Liquid

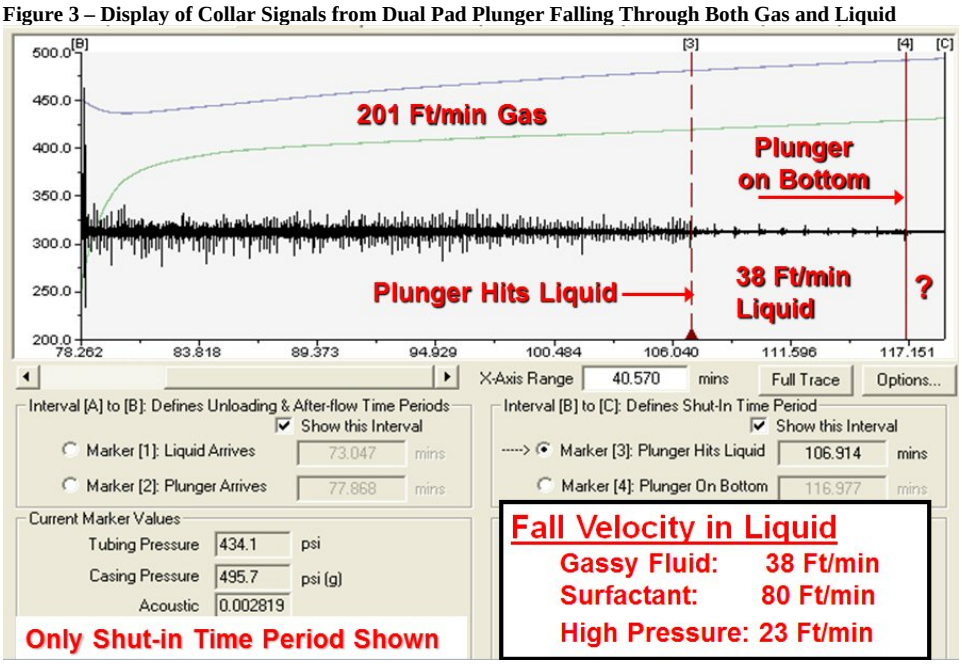


Figure 4 – Plunger Fall Speed between Two Consecutive Counted Collars

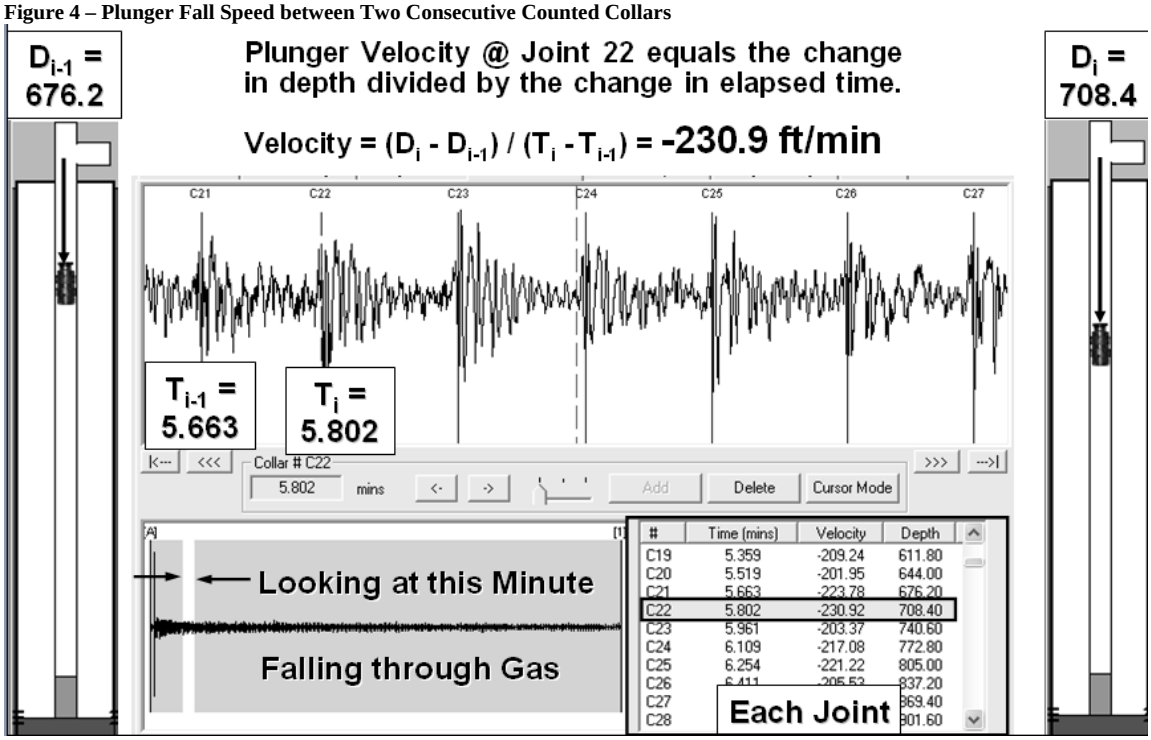


Figure 5 – Plunger Depth and Plunger Fall Velocity for a Typical Plunger Well

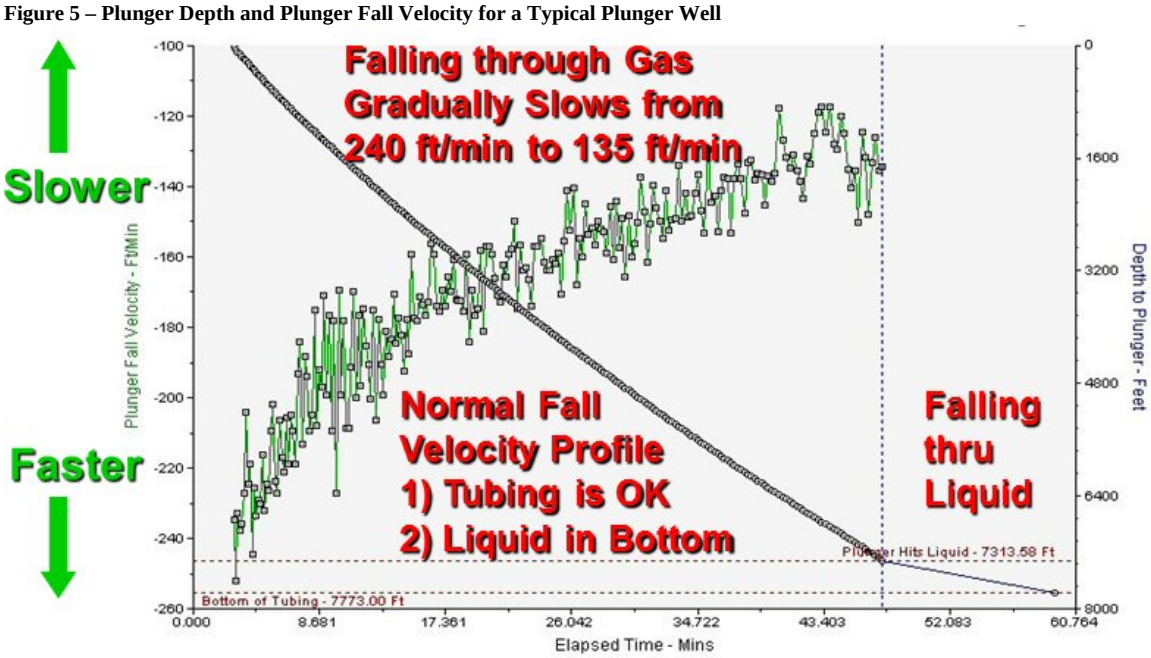


Figure 6 – General Plunger Fall Model Equates Plunger Fall Velocity to be Inversely Proportional to Density

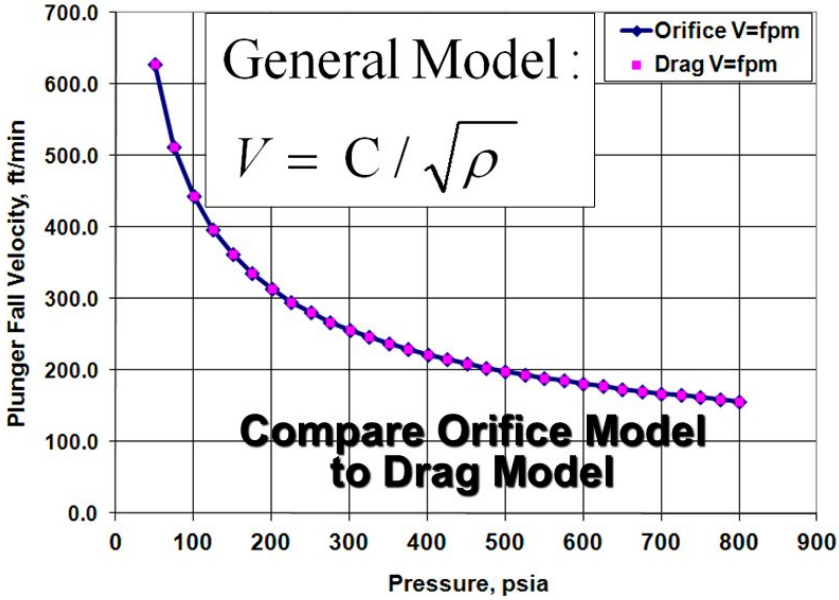


Figure 7 – Shut-in Tubing Pressure and Plunger Fall Velocity for a Typical Plunger Well

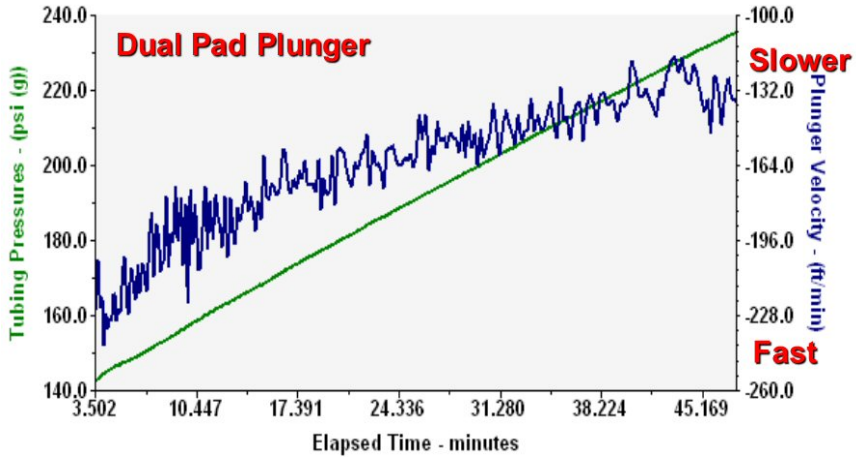


Figure 8 – Plunger Fall Velocity Increases as Tubing Pressure Decreases

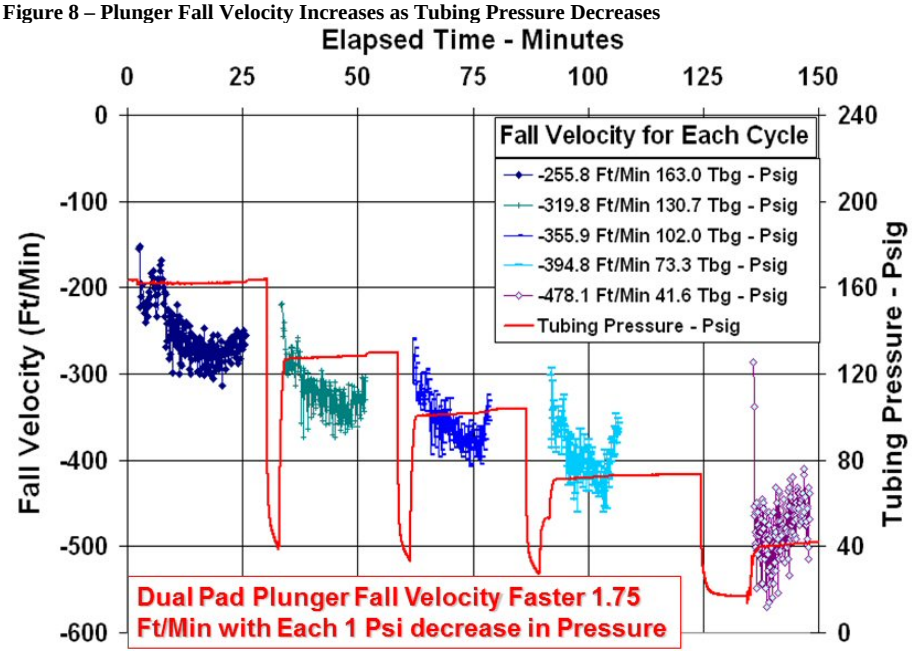
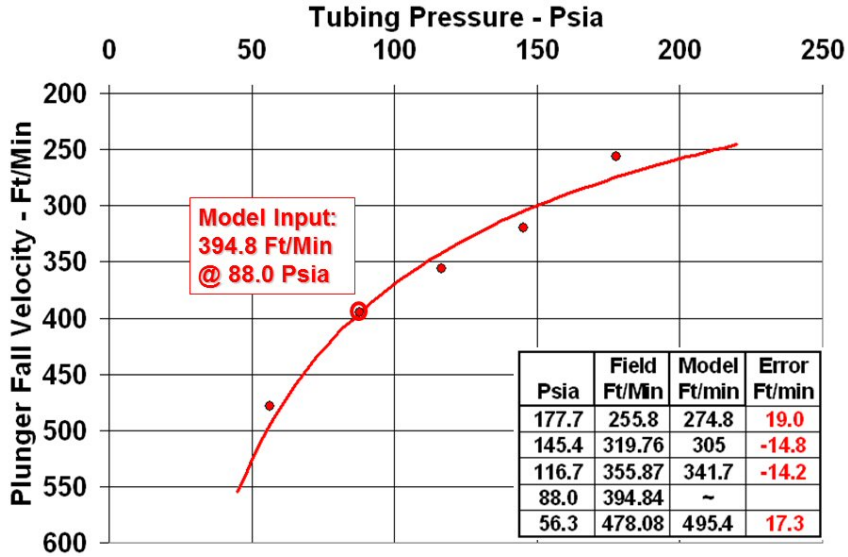


Figure 9 – Compare Fit of General Plunger Fall Model to Dual Pad Plunger at 5 Different Pressures



Psia	Field Ft/Min	Model Ft/min	Error Ft/min
177.7	255.8	274.8	19.0
145.4	319.76	305	-14.8
116.7	355.87	341.7	-14.2
88.0	394.84	~	
56.3	478.08	495.4	17.3

Figure 10 – Predicted versus Measured Plunger Fall Velocity for Solid Cleanout Type Plunger

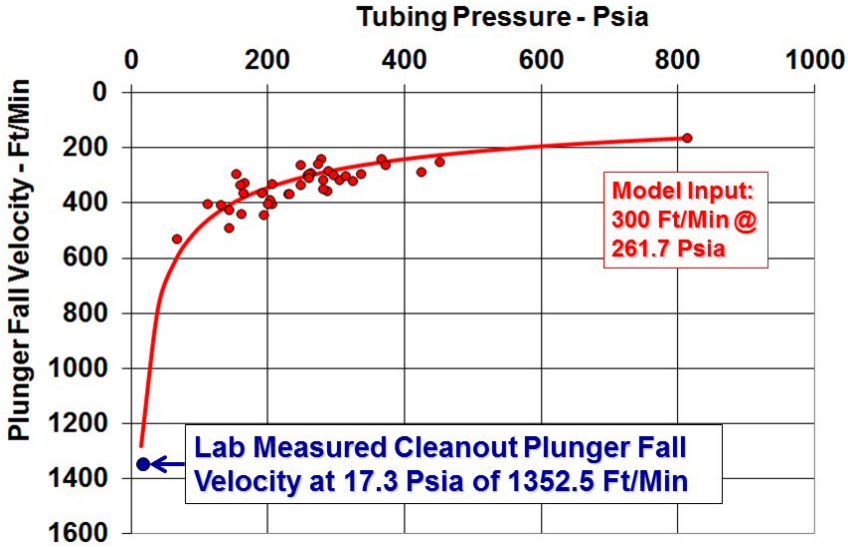


Figure 11 – Fall Velocity Plot of a Dual Pad Bypass Type of Plunger with Tubing Pressure 1732 to 2213 Psig

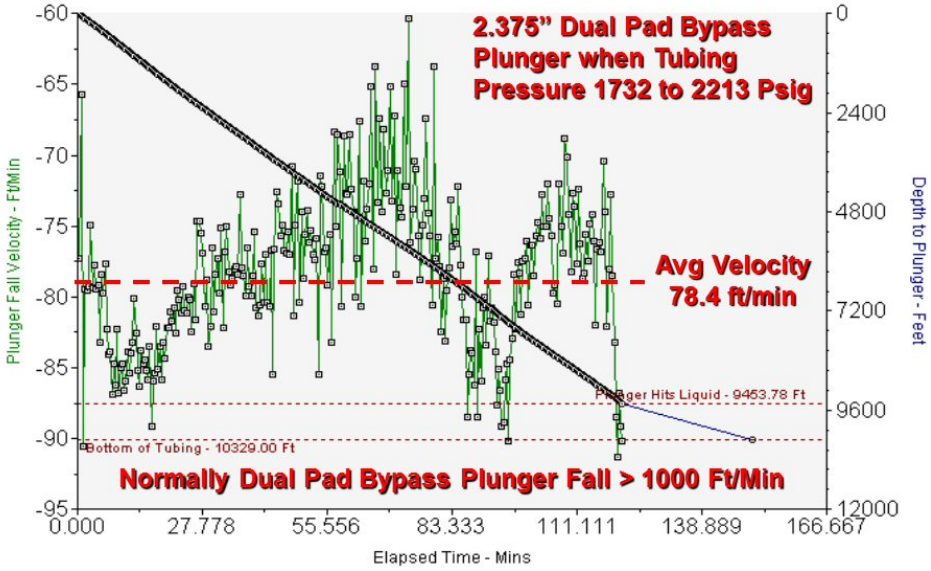


Figure 12 – Solid Cleanout Type of Plunger Slows When Entering Deviation

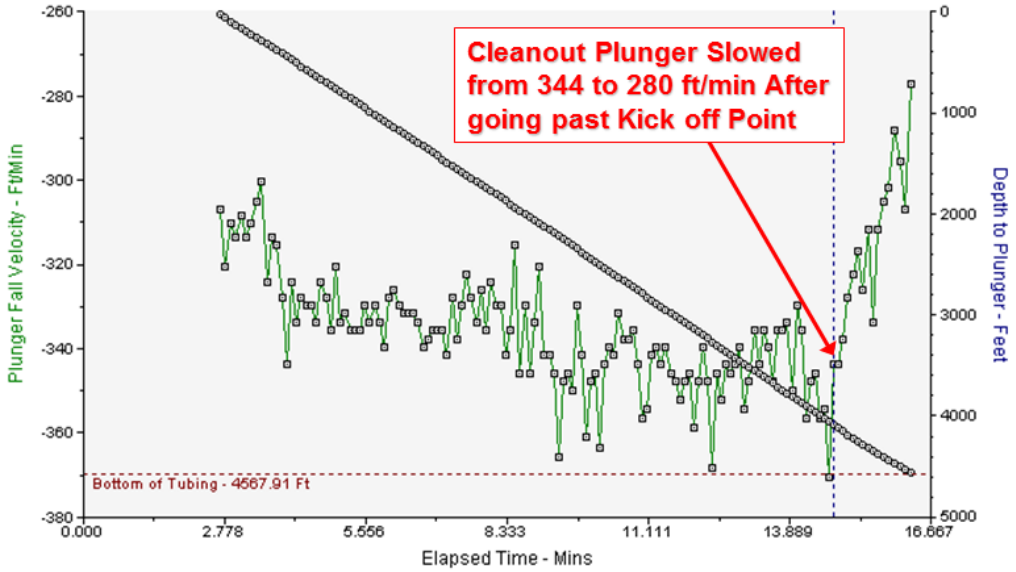


Figure 13 – Padded Type of Plunger Increase in Speed When Entering Deviation

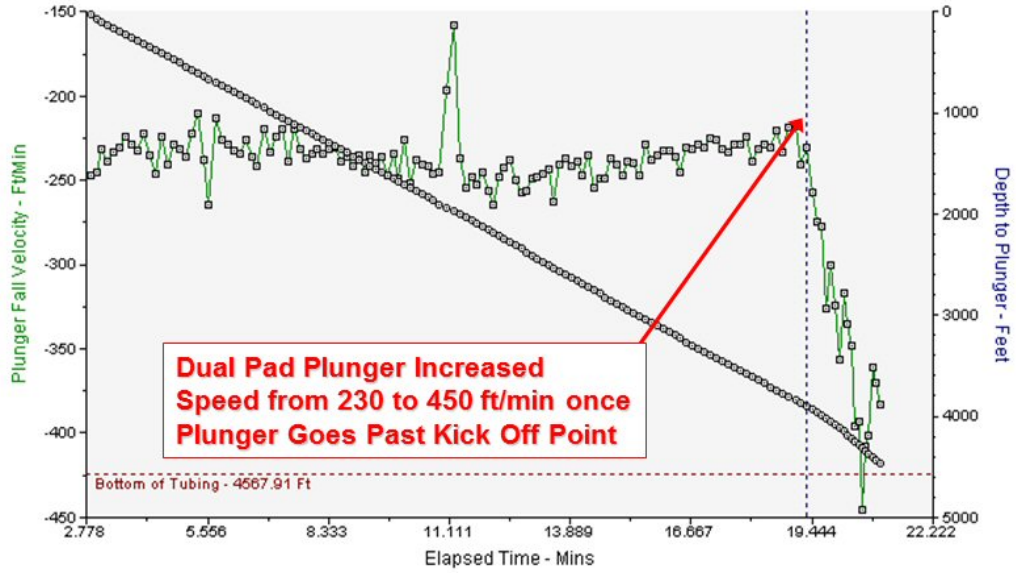


Figure 14 – Padded Type of Plunger Fall Velocity Increases at 20 Degrees of Wellbore Deviation[7]

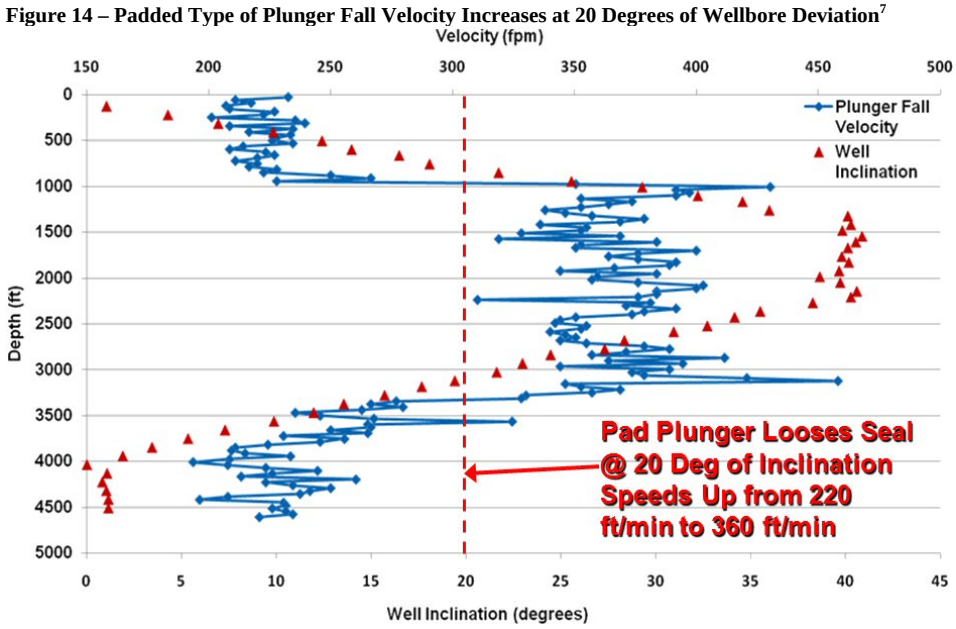


Figure 15– Increase in Instantaneous Gas Flow Rate when Standing Valve Opens Decreases Plunger Fall Velocity

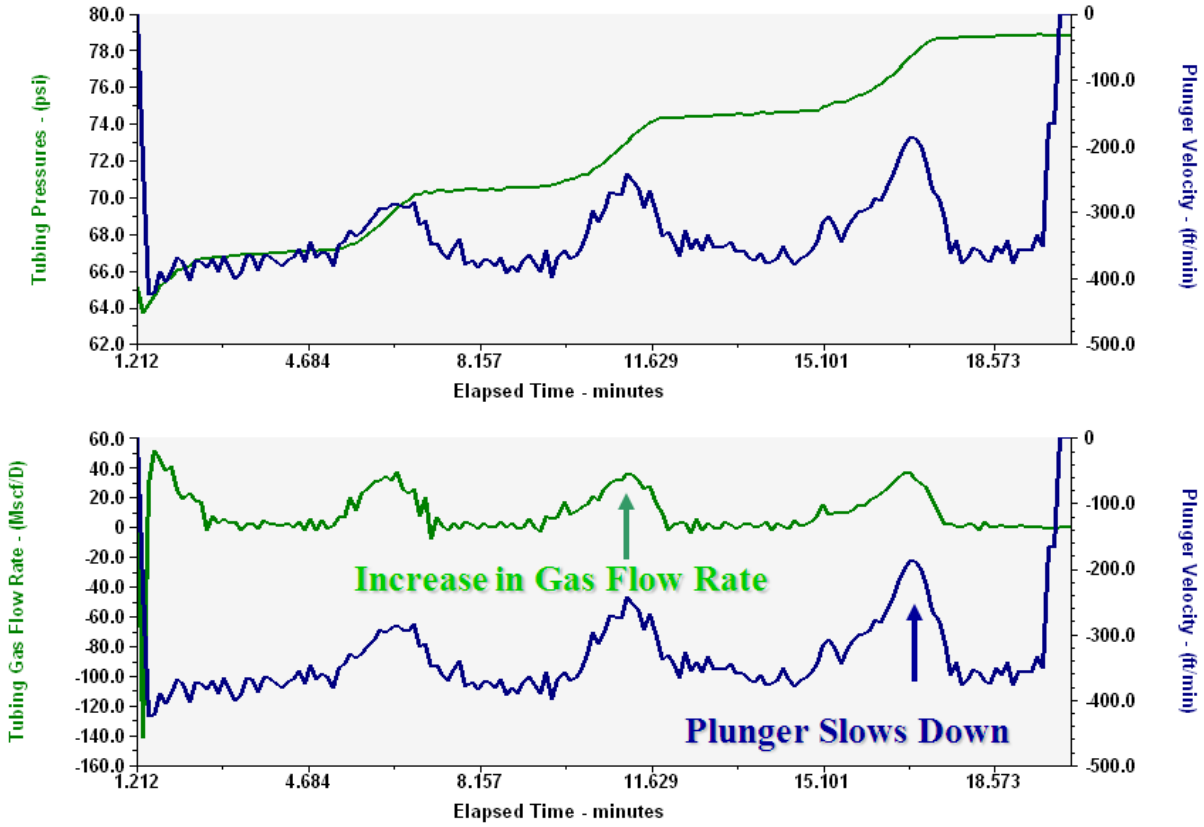


Figure 16 – Plunger Stuck, Stops and Tubing Pressure Suddenly Increased by 3 psi

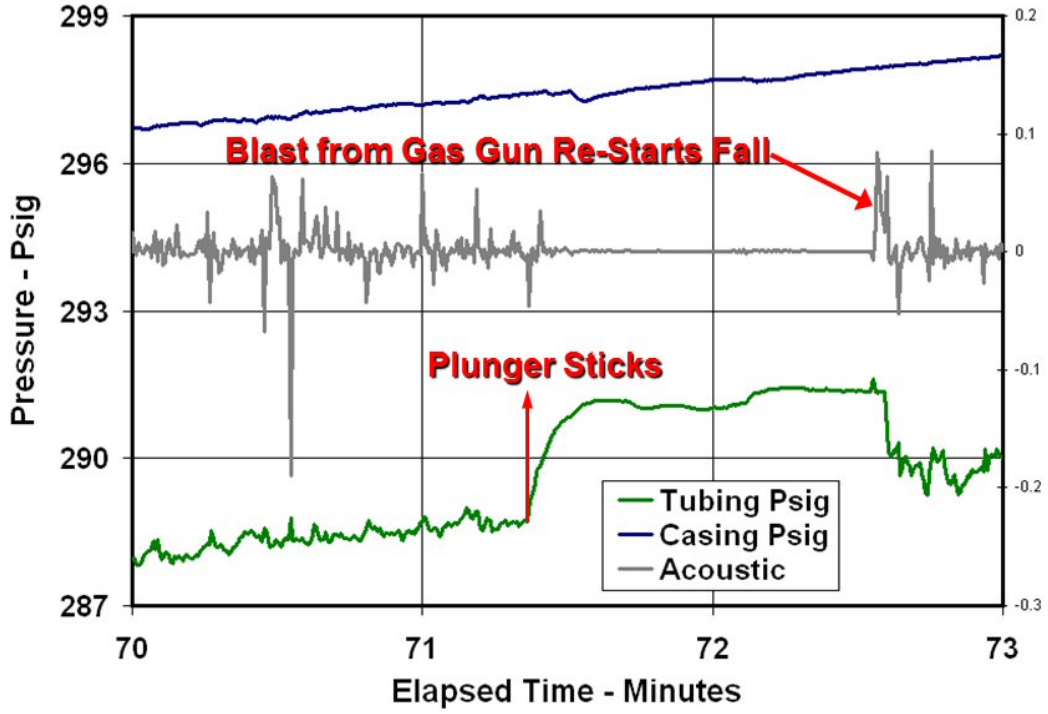


Figure 17 – Very Slow Fall Velocity due to Treated with Chemical down the Tubing

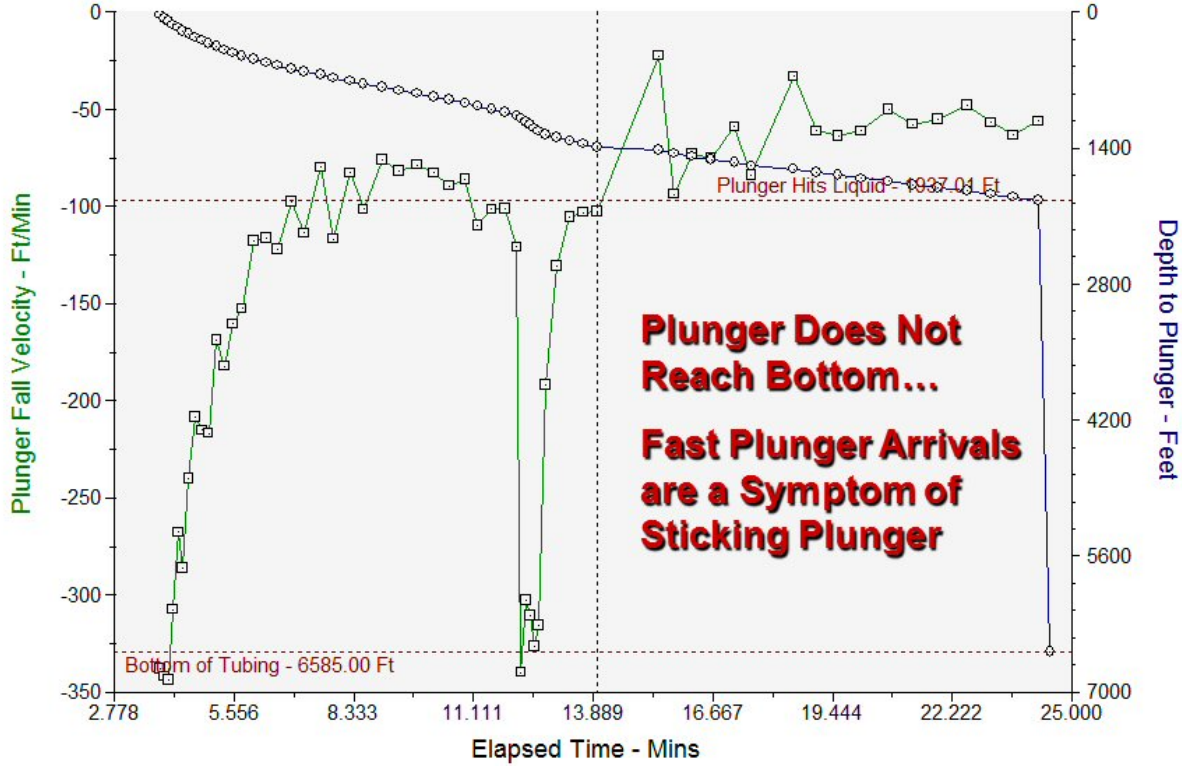
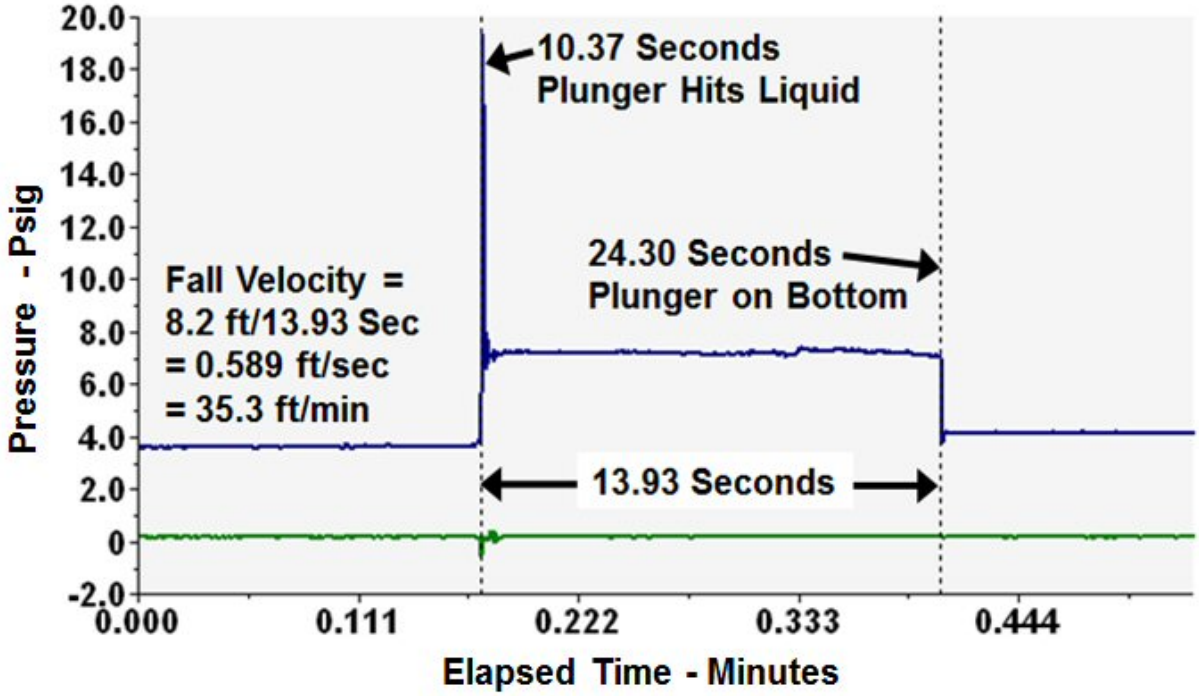



Figure 18 – Elapsed Time for Triple Pad Plunger to Fall Through Gas Free Water