SPE 147225

Analysis of Plunger Lift Applications in the Marcellus Shale

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This paper was prepared for presentation at the SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA, 30 October–2 November 2011.

Abstract

Field testing was performed on plunger lift systems in horizontal Marcellus shale wells. Plunger lift software from Echometer Company, Total Well Management, or TWM was used on certain wells to monitor acoustic trace, casing pressure, and tubing pressure throughout the plunger cycle.

The plunger lift testing program addresses the challenges presented in shifting from vertical to horizontal well plunger lifting. The plunger lift testing addresses the feasibility of running plunger lift on wells with X and XN-profiles. These nipples are used to provide safe snubbing operations. The most valuable insight from the testing involves the possibility of running plunger lift to deviation angles of 70° and greater.

The results of the plunger lift testing yielded several conclusions. An important result was that all plungers successfully passed through the X-profile, contrary to industry doubt. Another conclusion was that all plungers fell down to their bottom deviation angle with the deepest falling of 70°. Testing also showed the importance of performing TWM investigations on every plunger lift well to optimize plunger cycles. The most notable result was the phenomenon that plungers fell faster below kickoff point. This phenomenon suggests the possibility of plungers travelling to 90°. The observed trends of 53 TWM traces suggest that current plungers in horizontal Marcellus shale wells can theoretically reach a final deviation angle of 74°.

Plunger lift systems have been used across the United States for decades to unload small amounts of liquid (water, oil, and/or condensate) as gas rates fall below the minimum critical rate to continuously unload fluids. The Marcellus shale is a vital asset to natural gas production in the United States. Development has transitioned from a vertical well science program to a proven horizontal well development program. Plunger lift has become common among some operators in the Marcellus shale for wells which have fallen below their critical gas rate. Our plunger lift program shows promise to maintain production after wells reach unstable flow up the tubing. Marcellus shale production can potentially benefit significantly if plungers eventually reach deviation angles of 90° since it will allow for production of fluid left in the horizontal lateral.

Introduction

As the Marcellus shale progressed from a vertical well science program to a horizontal well development program, so has the selection of the appropriate artificial lift system (ALS). At the start of Marcellus shale field development, it was assumed that artificial lift selection would follow that of the Barnett shale (gas lift). However, increasing knowledge of the Marcellus shale shifted the ALS away from gas lift and rod pumping toward the use of plunger lift. Original Marcellus shale vertical wells did not produce enough water and condensate for effective gas lift and the cost of rod pumping proved to be too expensive. Nearly all the rod pumped wells were retrofitted with either tubing or casing plungers, and those wells adapted strongly to plunger lift. It was also realized soon after these installations that each well would benefit because the Marcellus shale wellbore pressures rebounded quickly during the shut-in periods due to their high initial reservoir pressure (>3500 psi). This quick turnaround in pressure support proved beneficial in running plungers.

During these field trials in vertical completions, more wells were being successfully drilled horizontally and hydraulically fractured. It became apparent that an ALS for horizontal wells would need to be addressed. Critical velocity (Turner) calculations suggested that wells with 2 3/8” tubing would need an ALS at rates of 300-500 Mscf/d at a casing pressures ranging from 100-300 psig. In early 2010, several horizontal wells were seen having unstable flow regimes and it was decided that they would receive plunger lift installations. Most gas reservoirs in the world go through a progression from initial production through casing, then tubing installations when flow becomes unstable, and then installation of the most appropriate ALS for the field’s reservoir conditions.

Several challenges with horizontal well plunger lift were addressed that were not present in the vertical well phase of field development. The first challenge came with the end of tubing, or EOT, typically being set at 70°. Another important challenge arose from the process of safe snubbing operations on tubing installations. Safe snubbing operations call for an X-profile nipple to be set at 10° and a XN-profile (no go profile) set at 70°. These nipples allow for a blanking plug to be set if the tubing needs to be pulled, which prevents any wellbore fluids from reaching the surface during these operations. The inner diameter (ID) of the X-profile nipple is 1.875” and the ID of the tubing is 1.995”. This meant that plungers would have to pass through the X-profile but retain their seal with the tubing enough to hold and bring a slug of liquid to the surface.

Plunger Lift Testing

Prior to accepting any plunger lift system as the standard operating procedure for the field, design testing was performed in horizontal wells using different plunger types to confirm their performance. Echometer Company’s software TWM was utilized to analyze each well’s plunger lift cycles in terms of the plunger fall velocities and fall depths. A detailed analysis of the software used and its applications is found in “Plunger Lift Optimization by Monitoring and Analyzing Wellbore Acoustic Signals and Tubing and Casing Pressure” (Becker 2006[1]). The testing program involves three specific measurements recorded by the real time testing equipment: acoustic trace, tubing pressure, and casing pressure. Each measurement is taken from the wellhead during the plunger lift cycle. **Figure 1** is a typical plunger lift cycle recorded by the testing equipment. The casing and tubing pressures are shown and the lines in the background show the acoustic trace, or noise, measured in mV. The cycle begins with the shut in, or SI, where the plunger is falling and both tubing and casing pressures are increasing. As the plunger passes through each joint of tubing, the collar recesses cause a noise wave to travel up to the surface where it is recorded. These collar spikes are used to determine the plunger’s velocity and travel depth. When the SI ends and unloading begins, the tubing and casing pressures drop and the plunger begins moving up the tubing. The tubing pressure will draw down until the liquid load carried by the plunger reaches the wellhead. The plunger then arrives at the wellhead and afterflow begins (gas is flowing to sales). The liquid and plunger arrivals are identified by the noise spikes in the acoustic trace. The afterflow part of the cycle continues until the controller settings begin the SI cycle again. These TWM data were used to evaluate different plungers.

Horizontal Plunger Lift Program

The challenge to running plunger lift in horizontal wells was to design a plunger system that would pass through the X-profile nipple and maintain an efficient seal to remove fluids from the tubing. We tried several plunger types like solid, brush, and brush/pad combinations, but all of these stuck in the X-profile. TWM software confirmed this as well. A few of the failed systems even required a rig to fish out the stuck plungers. The system that seemed to perform better comprised of two shortened pad plungers designed to pass through the X-profile. A two plunger system accounted for the chance of the bottom falling plunger sticking in the X-profile. If this occurred, the impact of the top plunger would free the stuck plunger from the X-profile restriction. The plunger used in horizontal wells was designed specifically to fall through the X-profile is a 2” outside diameter (OD) shortened single pad plunger (8” in length as opposed to conventional 12”). These plungers are comprised of one set of 4 equally spaced spring loaded pads which collapse to fall through the diameter restriction at the X-profile. When collapsed, the OD of the plunger is 1.860” and then when expanded, the pad OD is 2.000”. The idea behind the length reduction was to decrease the amount of surface friction between plunger and tubing allowing the plungers to fall further through the curve.

First, a single plunger was tested to confirm if the plungers did pass through the X-profile and reach bottom. Fall depth confirmation for this plunger lift system is shown in **Figure 2**. The final depth of the plunger's fall for this test was 6,350 feet of measured depth. This is represented by the last data point in Figure 2. The XN-profile for this well is at a depth of 6,352 feet measured depth, so the plunger travelled all the way to its final depth confirming this passed through the X-profile and reached the EOT and the XN-profile. This result also confirms that only one plunger was required to pass through the X-profile.

The next phase of testing was whether two plungers were more efficient. After looking at the acoustic trace of a one plunger test versus a two plunger test, the traces were very similar and the plungers showed very little separation during the fall cycle. The time between noise spikes of the two plungers was a mere few seconds confirming that the plungers fell on top of one another. However, during the unloading sequence, two different liquid slugs are seen at the surface instead of one when running two plungers. This means that some or all of the liquid that falls off of the top plunger is caught and brought to surface by the bottom plunger.

Another interesting result of this testing program came from an observation that the plunger fall velocity actually increased at the kickoff point, or KOP, of the horizontal curve. **Table 1** lists the fall velocities of a well with a KOP at 5,750 ft. Fall velocities were exported directly from the plunger lift testing software and show a significant increase in velocity near KOP. This is the same test as the fall profile shown above in Figure 1. The velocity just after KOP at collar # 183 is 141 ft/min and the velocity is almost doubled to a fall velocity of 279 ft/min just 200 ft after KOP. An increase in velocity at KOP is counter intuitive since we would expect the friction to increase between the plunger and the tubing, but there are a few important reasons that explain why this increase in velocity occurs.

During a typical fall sequence of a plunger in a vertical wellbore, the plunger's fall velocity decreases. The primary reason is that the drag force of the gas velocity increases the closer the plunger is to the source of the gas flow, the perforations. Since the plunger has a similar OD to the ID of the tubing, the plunger is somewhat centralized inside the tubing and the drag from the gas flow directly opposes the plunger's path. Laboratory testing performed by the plunger lift manufacturer shows that at KOP, the drag force of the gas flow opposing the plunger is reduced by 29%. The reason for this reduction of drag from the gas flow is because at KOP the plunger rests on the low side of the tubing. Since the plunger is on the low side of the tubing, the gas flow is directed to the high side of the tubing reducing the gas flow drag. So, at KOP, the plunger's resistance to fall is reduced and the plunger fall velocity increases. This result is significant because it encourages further testing for the potential of plungers falling to 90°. It is important to remove as much fluid as possible from the horizontal lateral of the wellbore, so if plungers can reach 90°, it may enhance the wells ability to do so.

The conclusions of this initial testing program are the following:

- A shortened spring loaded pad plunger can fall through the X-profile and reach bottom
- Two plungers were not needed to pass through the X-profile since both went through
- Two plungers produce more fluid than just one plunger
- Plunger's fall velocity increases at KOP suggesting potential to fall further than 70°

Testing for 90° Potential

The primary benefit of a plunger traveling to 90° is probably a reduction of water block on the formation, although lowering the tubing to 90° will also help reduce the bottom hole producing pressure slightly as water is more efficiently produced. If more water is removed from the lateral, there will be less water remaining in the hydraulic fractures system, which could help the relative permeability to gas. The water produced by the well is the water that was used for hydraulic fracturing, so it is best to remove as much of it from the lateral as possible.

The TWM software was used again to test how far plungers may potentially fall in a horizontal wellbore with the tubing placed within the curve. Six additional wells were tested for plunger acceleration, comprising a total of 7 wells and 53 tests. Testing began by analyzing a single well (9 tests) that best represented the plunger acceleration trends. This plunger installation was set with the XN-profile at an angle of 46° inclination, which was about 6,150 ft of measured depth (MD) from the surface.

Initial observations of the plunger fall velocities for this well show two distinct fall velocity profiles. The first profile is the plunger deceleration from surface to KOP which is typical of conventional plunger lift systems. A polynomial curve was fitted to the second trend which is the period when the plunger accelerates after reaching KOP before beginning its final deceleration as it reaches bottom. It is this trend that is extrapolated to determine how far a plunger would continue to fall, assuming the tubing was extended further into the curve in the future. The single well analysis is shown in **Figure 3**. The measured velocity is represented by the blue line and the two distinct trends of the data are shown in black.

Now that the data after the KOP is fitted with an accurate velocity trend, the trend is extrapolated to show how much further this plunger would fall if allowed to do so. The equation of this velocity trend was plotted against MD (known directional survey) for this single test. This extrapolated fall velocity is shown in **Figure 4**. The cutoff for plunger fall potential is the extrapolated depth and inclination corresponding to a velocity of 0 ft/min. Theoretically, a cutoff of 0 ft/min is accurate because plungers never truly fall with one continuous velocity and do not fall relatively fast to begin with. If the plunger typically speeds up and slows down and continues to inch its way further down the wellbore, then theoretically that plunger can continue to fall as long as it has a positive velocity. So, using a cutoff of zero for velocity, the data was extrapolated and compared to a depth and inclination value.

The dashed vertical line in Figure 4 shows where the extrapolated fall velocity of the plunger reaches 0 ft/min at a depth of about 800 ft beyond the KOP. The XN-profile is currently set roughly 400 ft beyond KOP at an inclination angle of 46°. The extrapolated velocity trend does not reach 0 ft/min for an additional 400 ft beyond its current set depth. In terms of inclination the extrapolated fall velocity does not reach 0 ft/min until 77° inclination. If the plunger was allowed to fall past its current set depth it would theoretically fall to within 20 ft of TVD from the top perforations. The single well example shows significant potential for plunger lift installations to angles closer to 90°. Now that the representative well showed significant potential, all 53 tests were analyzed in a similar fashion to come to a general conclusion for plunger fall potential.

Figure 5 shows the fall velocities of all 53 tests with the two distinct trend lines included as well. Just as in the single well case, the trends fit the data accurately, especially the data after KOP. The depths are recorded in measured depth beyond KOP. Since 7 different wells were used in this analysis, there are 7 different wellbore trajectories, so the velocity cannot be extrapolated to one single inclination. This meant that a composite survey had to be developed that trended the wellbore inclinations for all 7 wells. **Table 2** lists the depths of the X and XN-profile nipples as well as the measured depth from current XN-nipple to the top perforations for each well.

The equation of the fall velocity trend was plotted and extrapolated by the same method as in the single well case to where the fall velocity was 0 ft/min. The depth where velocity reached 0 ft/min was about 800 ft beyond KOP. This depth was then taken and compared to the composite survey of the 7 wells to see what potential inclination can be reached by the plunger. After this was done, the inclination was 74°, which is shown in **Figure 6**. So, the results from all tests taken showed slightly less potential than the single well example, but still show potential for the plungers to continue toward their top perforations near 90°. The average depth between the current XN-profile set depths of these 7 wells and their top perforations is 100 ft TVD and 400 ft MD. If the plungers fell to 74°, their average depth away from the top perforations would be 25 ft TVD and 225 ft MD. The test results show that the depth between the current XN-profile and the top perforations could potentially be reduced.

It is important to note that during the testing plungers only reached a zero velocity when they reached the XN-profile at the bottom. None of the plungers came to a halt prior to their bottom depths which alone shows potential that the plungers would have continued their fall. Also, when looking at specific well examples for this potential, the most significant limiting factor is the use of X and XN-profiles for safe snubbing operations. The inner diameter restriction of the X-profile limits the plunger type that can be run in the well. Since plunger lift systems are limited to shortened pad plungers, the fall velocities are limited to average fall velocities of roughly 200-300 ft/min. Without these profile nipples, different plunger types could potentially be used which fall at much higher velocities. For example, typical bypass plungers will fall with velocities of 1000 ft/min greater, about 5 times faster than shortened pad plungers. If similar analysis was done on plungers like these, the potential to fall closer to 90° could potentially be much greater.

Conclusions

Following are conclusions of all of the plunger lift testing performed.

- No test wells showed a velocity of zero prior to reaching the XN-profile at the EOT

- The single well example showed potential for the plunger to fall within 20 ft of TVD from the top perforations if tubing was lowered to this depth.
- All 53 tests combined suggest fall potential to 74° inclination.
- Tests show that if plungers continued to fall past their current set depths that they can fall to within 25 ft of TVD from the top perforations
- Testing will continue as wells have tubing and plunger lift lowered to the top of the perforations

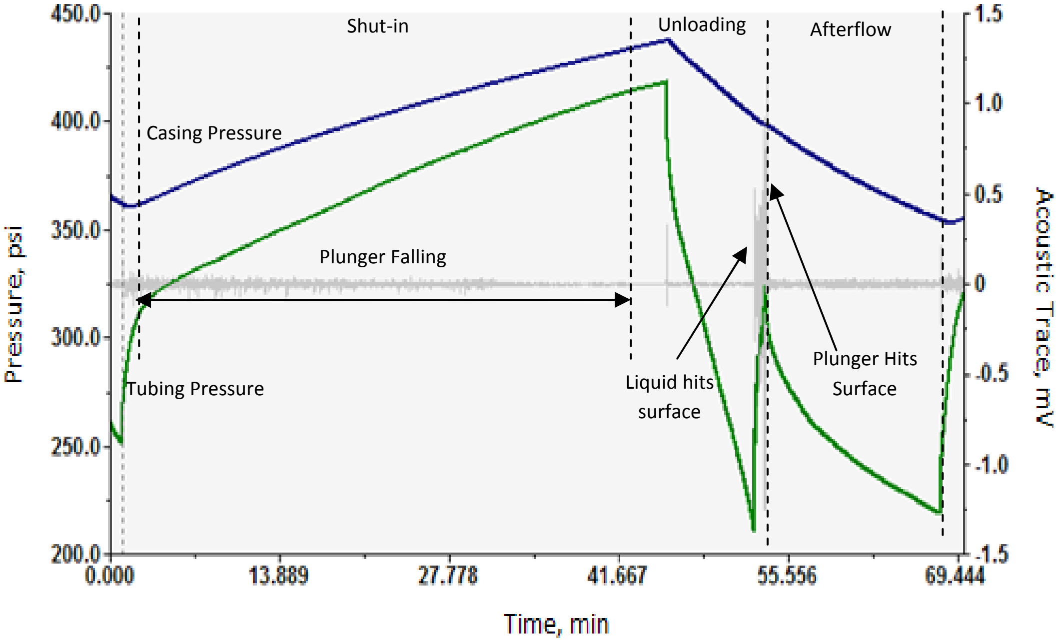

Fig. 1—Typical plunger lift cycle seen in Echometer's Total Well Management.

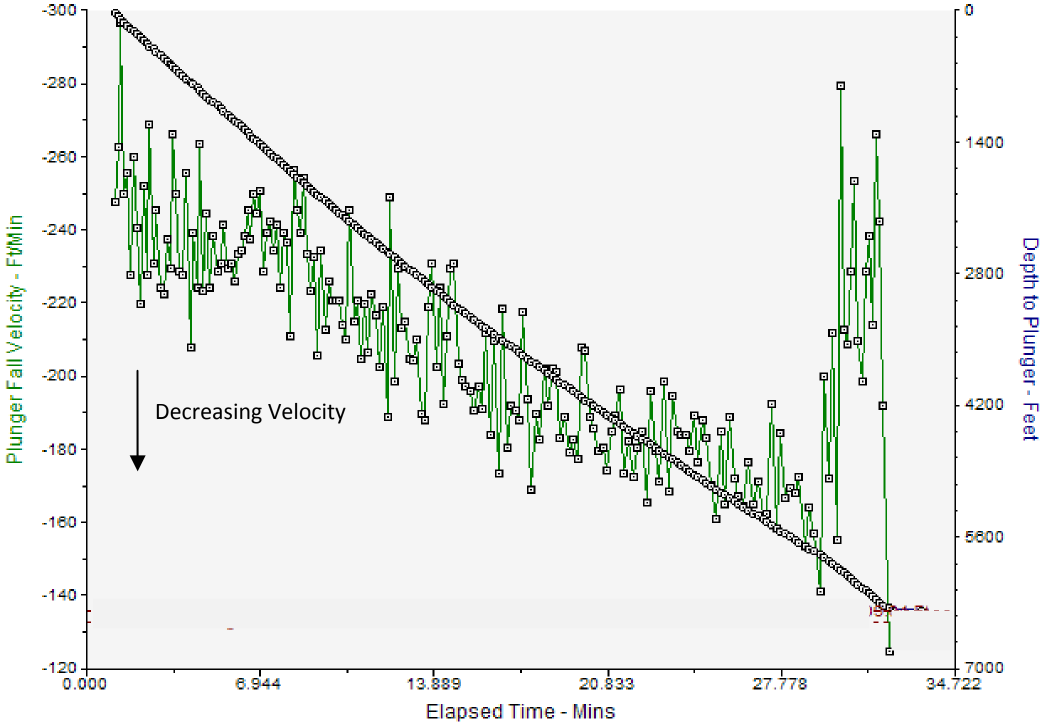

Fig. 2—Fall profile of plunger lift cycle showing fall velocity and depth versus time.

TABLE 1—PLUNGER FALL VELOCITIES BEFORE AND AFTER KOP.			
Collar #	Time, min	Velocity, ft/min	Depth, ft
C182 (KOP)	29.115	157	5759
C183	29.339	141	5791
C184	29.498	200	5822
C185	29.682	172	5854
C186	29.831	212	5886
C187	30.035	155	5917
C188	30.148	279	5949
C189	30.297	213	5981
C190	30.449	209	6012

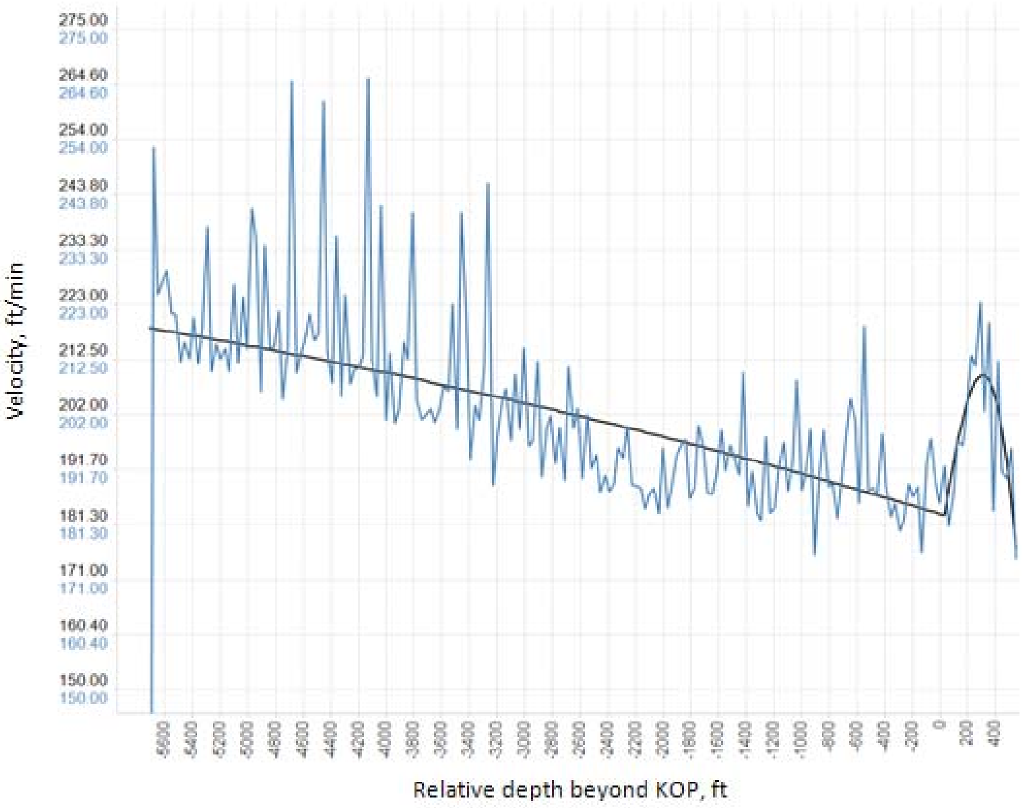

Fig. 3—Fall velocity trends plotted against relative depth beyond KOP for the single well example.

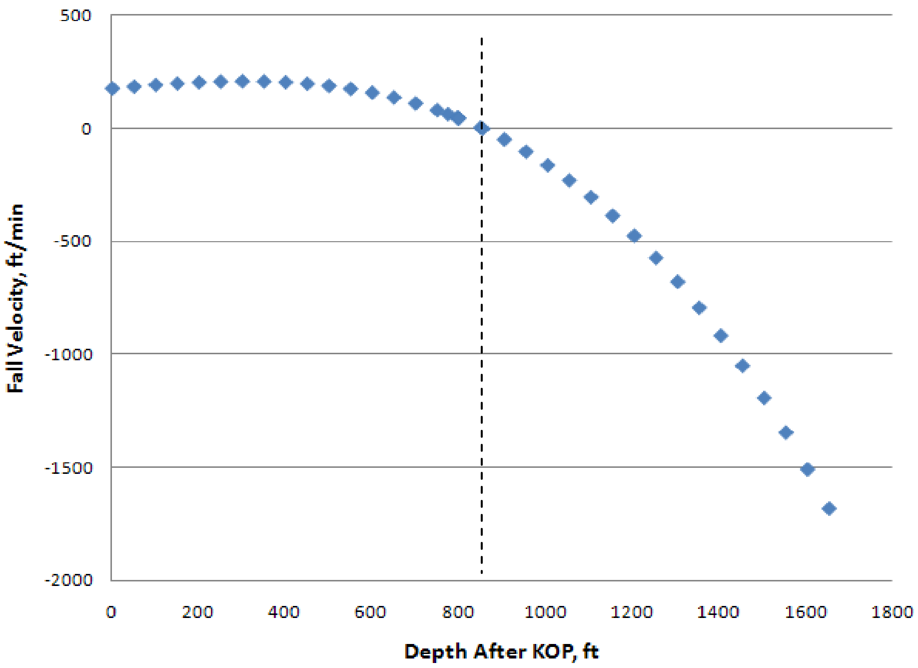

Fig. 4—Extrapolated fall velocity of single well example.

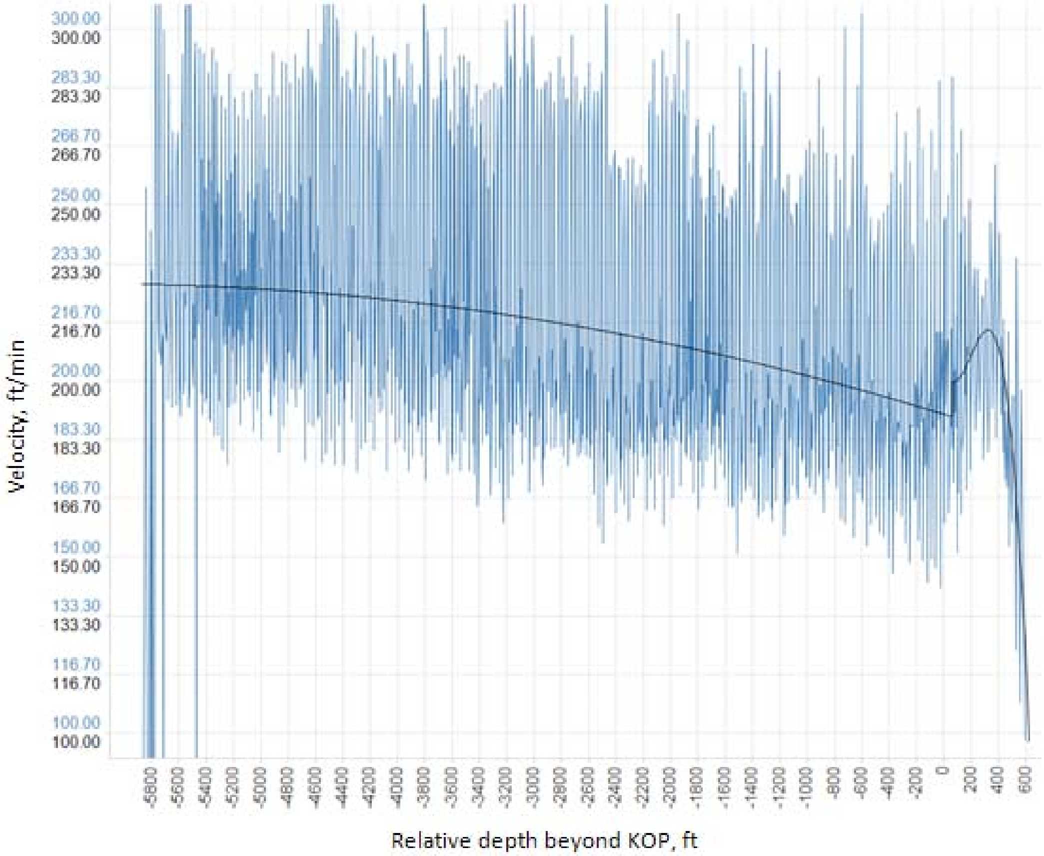

Fig. 5—Fall velocity trends plotted against relative depth beyond KOP for the all test wells.

TABLE 2—X-PROFILE AND XN-PROFILE DEPTHS AND DEPTHS TO TOP PERFORATIONS FOR ALL 7 TEST WELLS. DEPTHS ARE IN MD, OR MEASURED DEPTH.

Well	X-profile depth, ft (MD)	XN-profile depth, ft (MD)	XN-profile to top perf, ft (MD)
1	5463	6376	370
2	5750	6352	208
3	6001	6306	314
4	5674	6117	730
5	5893	6148	620
6	6007	6539	161
7	5940	6276	424

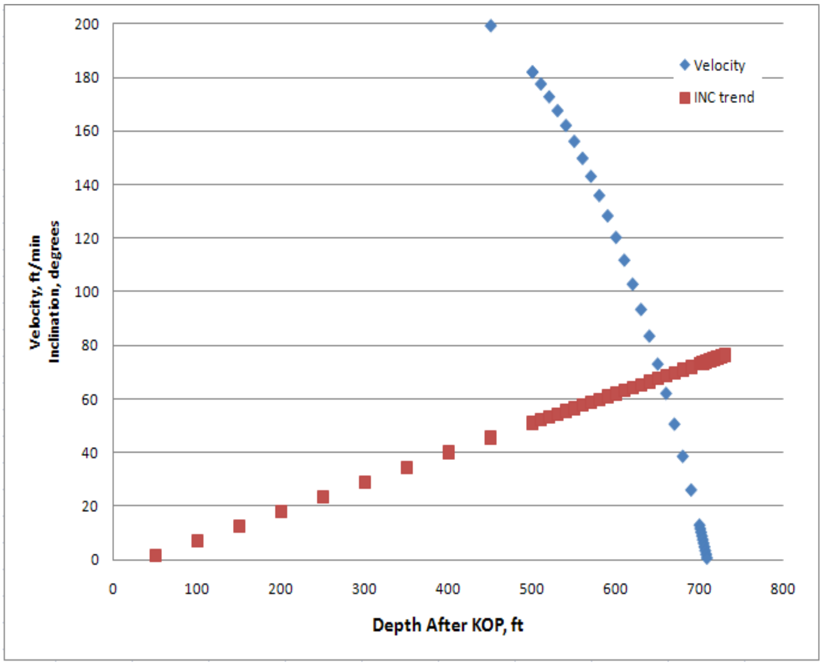

Fig. 6—Extrapolated fall velocity and inclination of all 7 test wells.

References

1. Podio, A.L., McCoy, J.N., Becker, D., Rowlan, L., and Drake, B. 2001. Total Well Management II. Paper SPE 67273 presented at the SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA, Mar. 24-27.