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Improved CT Well Cleanout and Milling Procedures Utilizing Only Non-Viscous Cleanout Fluids

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Abstract

The use of coiled tubing service in the shale market has been of great importance in the process of preparing O&G wells for production, mainly in the post-fracturing isolation plug milling and solids cleanout. The challenges that the coiled tubing (CT) industry has been facing are substantial and range from CT pipe manufacturing and related technical matter to logistic and operational conditions. The CT industry has worked relentlessly to remain competitive both in efficiency and economic terms in comparison with new competitive completion techniques.

Well cleanouts are by far the most common operation performed with coiled tubing on a worldwide basis and also one of the most complex operations due to the large amount of operational variables involved. The shale market experiences the very same scenario, and cleanout-milling activity is far from flawless. Substantial amounts of solids, mainly the heavier ones, remain in the wellbore after the cleanout operation is completed.

Some of the traditional and deeply rooted techniques utilized in well cleaning nowadays have their origins in drilling and work-over operations in vertical wells. Some new important techniques presented in this paper, primarily addressing operations in horizontal shale wells, helped to improve overall efficiency during cleaning-milling operations.

These new techniques involved advanced cleanout procedures coupled with the utilization of non-viscous fluids throughout the operation. Use of viscous fluids was completely eliminated from the operations and even for contingency plans in critical scenarios, such as high-drag or near-stuck conditions. When most of the wellbore clean out parameters were optimized, hole-cleaning performance was significantly better when eliminating viscous pills and controlling the chemical dosage.

This paper also describes the importance of proper plug milling/well cleanout and how this was attained. As milling and cleanout procedures have a direct influence on each other's performance, it is imperative first to optimize each one to maximize overall performance.

Likewise, other operational aspects are discussed here such as the importance of RIH/POOH speeds, bottom-hole assemblies (BHA), the effect of proper formation balance on the overall results and also the advantages of using non-viscous fluids from logistic, economic and environmental viewpoints.

Introduction

Well cleanouts are the most common type of service performed by the CT service industry, accounting for over 50% of all coiled tubing operations on a worldwide basis. While well cleanout covers a wide range of activities. In this exercise, we will concentrate in the solids, proppant, and milling debris only. Among others, some of the primary goals of such operations are to remove solids from the wellbore to improve well production and recover access. While cleanout interventions are historically common during the production phase of a well, i.e., as a workover solution, in the last few years it became part of the daily operations in North America in the pre-production, or completion phase, of horizontal shale oil and gas wells associated with the post-fracturing plug milling and cleaning operations. Even though the focus of this discussion is in the shale market, the concepts discussed are valid for all other cleaning scenarios, whether in post-fracturing or workover operations.

What Affects Cleanouts?

Cleanout design and performance are functions of the following parameters:

Conditions challenge, which may be difficult to fully determine

- Geometry - including the diameter of the casing, the completion and the well survey
- Down-hole pressure and to a lesser degree, bottom-hole temperature
- Shape and density of particles to be cleaned
- Isolated or clustered particles

Operational: parameters are easier to control and include the following:

- Diameter of CT pipe being used
- Length of CT string being used
- Fluid Pump rates
- Fluid types and characteristics (these can vary dramatically during operation)
- BHA
- Cleanout procedures

It is important to note that these are the minimum parameters necessary to establish a proper cleanout procedure and selection of appropriate equipment and materials. There are more parameters, conditions, and/or variations within these parameters and other aspects that are not taken into account in the currently available design tools and operational procedures that could affect cleanout final results. This is why operational procedures must be conservative and applied in order to offset any unknown effects.

Geometry

Geometry, in particular tubular size and deviation, are the parameters that define how almost all the operational parameters are determined. For any given rate, the tubular size will determine the annular velocity and flow conditions that develop in the CT-completion annular area. The larger the completion's internal diameter (ID), the greater the challenge to obtain adequate annular fluid velocity. Deviation is the other critical parameter. The challenges and the techniques leading to a successful cleanout are different if a well is vertical, horizontal, or deviated. In the oil and gas industry, some of the techniques were developed and matured while cleaning vertical wells and were adapted to clean horizontal wells with less impressive results. It is common when trying to access a horizontal well in which cleaning has just been completed to find out that a considerable amount of solids that were not transported to the surface and are still at the bottom.

Downhole Pressure

Downhole pressures ultimately determine the density of the cleaning fluid to be used to keep full fluid columns and properly transport solids from wellbore to surface. Low-pressure or depleted wells may not support a full column of liquid and may require the addition of a gaseous phase such as nitrogen. Importantly, levels of overbalance or underbalance will govern annular velocities and cleanout efficiency.

Particle Shape and Density

In many cleanout operations, the shape of the single or clumped-together particles being lifted at the bottom and transported to surface is not entirely known. The fluid viscous forces acting on the surface area of the particles are maximized on round particles. These round particles are transported because of the maximized surface area per volume ratio, the round particles are transported more readily than other shapes. In addition, induced rotation imparted by fluid to a round particle only partially hinders inertia or ability to move as it spins. Less round or differently shaped particles pose greater challenge to being picked up from completion walls and transportation of these particles in the fluid is more difficult. These particles continuously accelerate and decelerate or even stop as they rotate along their own axes, so they require more time and energy than round particles to travel similar distances. Fluids that can impart higher shear stresses are critical in cleanouts. The density of a given particle is another important characteristic because the higher the mass, the lower the imparted acceleration provided by a given fluid via the transfer of moment and viscous forces, which depend on its rate and rheological properties.

Operational Parameters

The operational parameters are the conditions created by design in a given well to maximize cleanout efficiency.

Coiled Tubing Size Logistics and cost permitting, larger outer diameter (OD) coiled tubing strings will assist in the cleaning as higher fluid annular velocities will be possible, for a given fluid pump rate, as result of a smaller annular cross section area. The smaller cross-sectional area will induce a higher annular friction pressure and CT OD size and pump rate optimization can be achieved by computing simulations. Another advantage of larger OD pipes is naturally the possibility of maximizing pump rate inside the CT for a given pressure drop assisting on the cleanout efficiency and providing better control over the operational CT pipe fatigue life.

Fluid Pump Rate This is the ultimate design parameter in order to obtain an effective cleanout. Fluids rates are maximized based on the optimization of other parameters such as flow cross-sectional area, fluids' rheology and fluids' characteristics, size and length of coiled tubing string, downhole pressure, pressure balance at bottom, among others. In vertical wells cleaning, the physics of particles transportation provides a wider combination of fluids velocity-fluid rheology, favoring viscous fluids, in comparison to highly deviated and horizontal wells. However, in either case, higher fluid velocities is the technique for faster and more complete cleanouts.

Fluid Characteristics As mentioned in the discussion of fluid pump rates above, fluid characteristics are extremely important. Fluid characteristics depend on the well scenario. A properly designed and monitored fluid will increase the efficiency of the entire operation, improving solids removal from wellbore and significantly reducing operational times and overall associated costs. The characteristic that requires most attention is rheology, and it must be adjusted in a way to combine the highest fluid pump rate with the smallest possible generated friction pressure for any given well geometry. The cleaning of vertical wells does require more- viscous fluids whereas the cleaning of highly deviated and horizontal wells can benefit from less-viscous fluids. In contrast to high-viscosity fluids, low-viscosity fluids can generate a higher shear rate at the tubular walls and develop a turbulent flow pattern (represented by Reynolds number) more readily. A more thorough discussion on rheology properties is presented later in this paper. In summary, proper fluid characteristics assurance and monitoring are of extreme importance during operations and neglecting these leads to poor results.

Bottomhole Assemblies (BHAs) Downhole tools can have a substantial impact in on the cleanout efficiency. This impact is the result of improved fluid dynamics at the leading edge of the BHA. As an example, some downhole nozzles are engineered to maximize the effects of turbulence combined with the ability to impart to solids a high hydraulic thrust in the same direction as the flow. This not only minimizes the residence time of solids in the vicinity of the BHA, but also increases the mass of solids removed by unit of fluid volume pumped at a given rate condition when coupled with proper procedures. However, it is important to observe that the hydraulic effects, or area of influence of the BHA on the particles in the wellbore are only felt within the fluid stream for a few feet above the BHA. Above this region, the particle movement and transportation are taken over solely by the fluid and the generated shear stress. In many wells, solids are not loosened or free to move by the simple hydraulic effects of fluid jetting, and a mechanical operation, such as a motor and mill combination, is required. Downhole motors do require power to operate, and this power is extracted from the fluid being pumped. Consequently, the hydraulic horsepower (HHP) available within the fluid is reduced (generally reflected by a lower fluid pump rate). Such condition asks for additional measures, generally operational, to effectively transport the solids to surface in a reduced-HHP scenario.

Another important example of the effects of BHA is on milling performance. Milling process performance is measured by how fast and effectively an existing mechanical restriction, such as consolidated solids or a mechanical plug, is removed. In the process of milling, the use of motors of various torque capabilities and mills of a variety of designs can generate debris of diverse size and shape. The milling BHA and milling procedures can determine the size of this debris, which, in turn, can directly influence in the cleaning efficiency and results. It is preferable to generate the smallest particles possible to maximize cleaning performance.

Cleanout Procedures Many variables must be identified and measured during a well cleanout. These variables can only be controlled using an engineered operational procedure. The operational procedure not only provides the regular steps to be followed during the course of a cleanout but also offers the correct contingency steps in case the real-time operational results are below expectations. Therefore, the operational procedure is the most important aspect of any planning. The procedure assembles and consolidates the overall operational goals with all the inputs, such as well characteristics (survey, geometries, downhole pressure conditions, particles to be removed, etc.), the tools, the fluids, and all the surface equipment available for a successful operation (Fig. 1). This procedure harmonizes all the operational aspects into a single process to maximize efficiency. Operations in which substantial resources are available but efficiency is low due to lack of a good procedure or lack of adherence to established and engineered procedures are common.

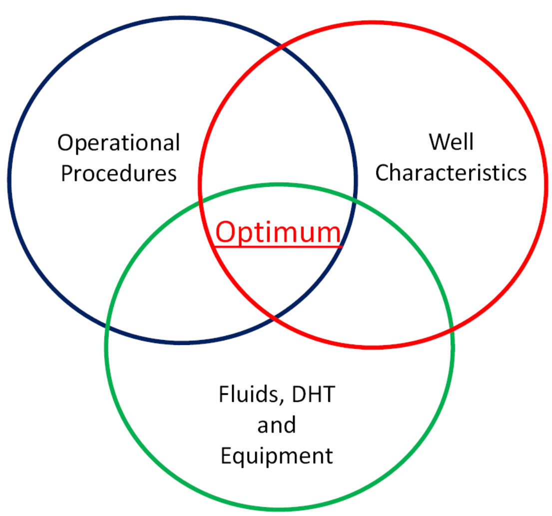

Figure 1—Wellbore cleanout variables.

Cleanout Technical Considerations

As already mentioned, cleaning efficiency in a given well can only be maximized when the best combination of equipment, fluids and operational procedures is applied. The challenging scenario of a horizontal well is of particular interest for particles transportation as it combines three very distinct zones or sections: horizontal, vertical and build-up sections. Particle transport and movement behavior changes substantially in each one these three distinctive zones as seen in Fig 2.

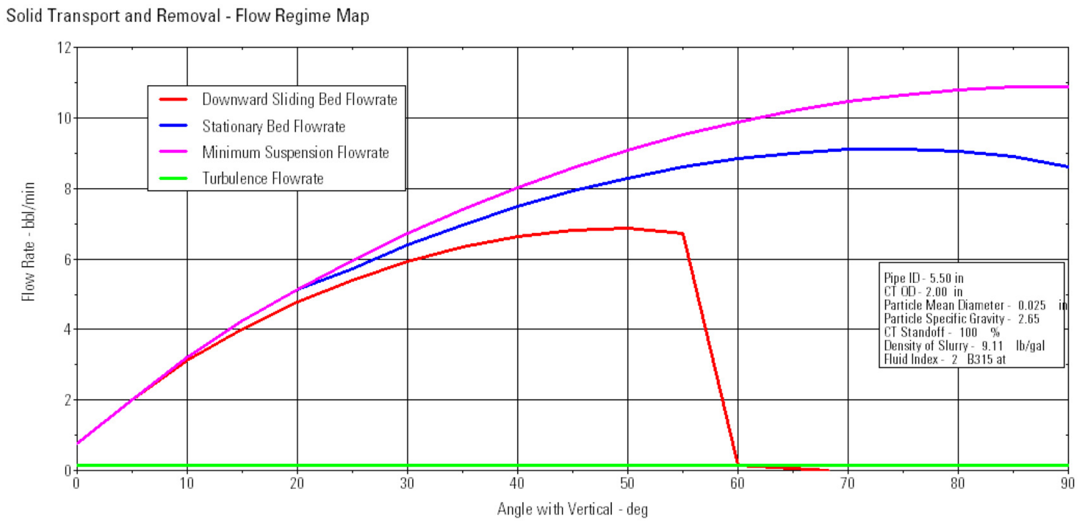

Figure 2—Particle behavior in horizontal wells in 2-in.-OD CT (5.5-in. casing).

The simulation above was performed for a 2″ OD coiled tubing pipe being run in a 5.5″ monobore horizontal well to complete a sand proppant cleanout. This simulation helps to show the behavior of particles in the wellbore according to the wellbore deviation and cleanout fluid pump rates practiced. Before advancing any further, it is convenient to introduce the concept of particles minimum suspension flow rate. This is the minimum flow rate (in the annular CT-Completion gap) that generates annular velocities (AV) in which no solids settle out and accumulate in the wellbore, being all particles continuously transported with no ″dunes″ build-up during the cleanout operation. As it can be seen above, the minimum suspension flow rate, for a given fluid, is function of the wellbore deviation angles. The greater the deviation, the greater the required rate: for the shown scenario (Fig 2), annular rates in excess of 10 barrels per minute are necessary to clean particles from the 90 degrees section on ″minimum suspension rate″ what is obviously a considerable challenge for the coiled tubing industry. Looking at the particularities in more detail:

Vertical Section

In the vertical or slightly deviated section of a well, the particles, in general terms, can either travel upwards (flow rate above minimum suspension rate) or downwards depending on the fluid rate. Particle fluidization (particles floating in place) is also considered a non-transport situation. This means that if the fluid velocity (annular velocity in the CT-completion annulus area) is higher than the settling velocity of the particle within the same fluid (at the current rheological conditions), it will be transported to surface. Otherwise, it will settle down and move downwards in the vertical wellbore. The forces acting on a particle are its weight, its buoyancy, and the drag force exerted by the fluid flowing around the particle as it settles within the cleaning fluid. In a very simplistic manner—spherical body, no particle rotation, no particles hindering, no particles clustering, laminar flow— the acting forces can be represented as in Fig. 3

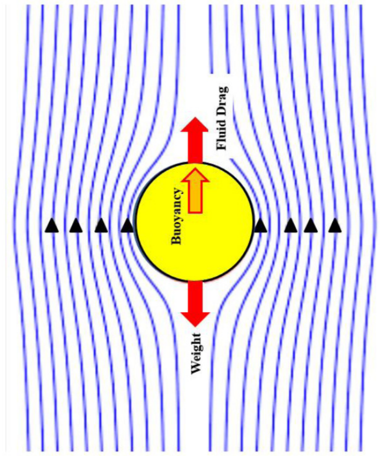

Figure 3—Simplified flow pattern around a solid and the acting forces

Another important consideration in the vertical wellbore section is to reduce the particles settling velocity within the cleaning fluid by increasing its viscosity. Therefore, the added viscosity will allow particles transport at lower fluid flow rates or annular velocities. This is particularly advantageous in large ID completions or when cleaning larger and heavier particles. While not always is possible to determine how the particles will interact with each other during the cleaning process, it is fair to assume that particles hindering and particles ″bundling-together″ will have a higher settling velocity.

Horizontal Section

In the horizontal or highly deviated sections of the well, the particle dynamics are substantially different from those in the vertical section. This is reflected in the high values of the minimum suspension flow rates, which, in practical terms, are not attainable (Fig. 2). Even flow rate values for the stationary bed flow rate shown in Fig. 2 are out of reach in most situations, even with larger OD CT strings. Particle saltation dominates the dynamics in the horizontal section. As the minimum suspension rates are not a possibility, the cleanouts should be performed at the highest flow rate possible. During most of the operation, particles move along the horizontal section by the fluid momentum transfer plus viscous forces imparted by the cleaning fluid. The settled particles are picked from the lower side of the completion/casing tubular by the shear stress generated by fluid eddies on the particle surface. Particles are accelerated and travel along the horizontal for a certain short distance before they strike completion/casing, CT walls, or even other particles, and are greatly decelerated. Then, the fluid picks up the particles, imparts movement/acceleration, and the particles travel again for certain distance. The process is repeated hundreds or even thousands of times until the particles travel all the horizontal section and reach the buildup section of the wellbore.

This relatively long travel along the horizontal is greatly affected by the fluid flow behavior (laminar or turbulent) and job procedures (CT speeds, short trips, etc.).

Fluids flowing in a laminar regime, due to their inherent lower fluid velocity and/or high fluid viscosity, generate lower levels of shear stress onto particles and when particles end up striking the lower side of the completion due to gravity, they stay there longer periods of time. This renders the entire transport process very slow and tedious, requiring additional operational procedures, such as short trips along with BHAs with improved hydraulic performance, to better stir particles as they are transported, to accomplish the cleanout task.

On the other hand, due to the associated high velocity, a fluid flowing in a turbulent regime can exert higher shear stress on particles and, with its potent stirring of turbulent eddies, the fluid can pick up particles easily, impart high average speeds to particles, and facilitate transport distances. It is important to mention that although the average particle speeds are much higher in turbulent flow, particles still strike each other in the tubular walls in the well due to the random behavior of turbulent eddies and being heavily decelerated. However, the same eddies make the particles go back into the main stream, and they are rapidly accelerated again. Therefore, the higher the turbulence imparted to fluid, the better for the particle transportation process. Higher turbulence levels are only possible with fluids that present lower rheology and viscosity.

This lower rheology, also generates lower pumping pressures, helping to protect the CT pipe from excessive pressures and fatigue evolution. Naturally, at the levels of turbulence targeted for these operations, even a low rheology fluid will generate substantial friction pressures, and this must be addressed with fluid friction pressure reducers that further adjust rheology. The efficiency of a properly generated and maximized fluid turbulence can minimize or even eliminate the use of operational assistance, such as short trips: particles will still strike the wall and decelerate, but simply adding circulation time will maximize efficiency and operational costs. There is further discussion on turbulence and Reynolds number in the rheology section of this paper.

Buildup Section

This is by far the most difficult and tricky area in any horizontal wellbore cleanout. Exacerbating the efficiency issue is the fact that this spot is the most neglected wellbore spot in the vast majority of cleanouts. From Fig. 1, it is possible to observe a particular behavior at deviations ranging from about 40 to 60°. Outside of this range of deviations, the process dynamics fall under vertical or under horizontal patterns. In this range of deviations, a new concept, the ″downward sliding bed flow″ is present. This concept means that if rates are below this threshold flow rate, the particles coming from the horizontal section that have reached the buildup, not only will not be transported to the vertical section, but they can simply slide back to the horizontal. Soon, they go back to the buildup area and accumulate in the curvature again in a rotational pattern. At flow rates above the downward sliding bed threshold but below the stationary bed flowrate threshold, particles will simply remain stationary in the buildup area in despite of continuous flow rate pumping. This phenomenon explains why so many solids are encountered in the buildup area in CT runs done after the cleanout and during workover operations; production rates are not high enough to effect the particles' transportation to surface. The reason particles tend to accumulate in this transition zone is due to the change in moving direction of the solids bed. The particles are traveling with a strong horizontal velocity component and, because their density is higher than the fluid density, their momentum makes them continue to travel horizontally and hit the curved casing and CT walls. The horizontal component of the particle velocity is abruptly reduced as the particle strikes the lower side of the casing/CT walls in the (long) curvature. As particles start to develop a vertical component, they then start to strike the upper side of the casing /CT walls. Centrifugal forces in the curvature also play a role. After striking the walls, the particles bounce back into the fluid stream, but centrifugal forces continue to send particles into walls.

Along with all these chaotic events taking place at the curvature, if even a small bed of solids is present in the lower walls, its softer mechanical properties will cause traveling particles to decelerate even faster than they would if particles were to strike a clean metal wall. This will reduce the particle average speed in the curvature, thus assisting in further accumulation and particle clustering.

Although the required pump rates to fully suspend the solids at these deviations is not quite as high as for the horizontal section, they remain quite difficult to generate.

Therefore, the best way to address the challenging solids transportation at the buildup is to use highly turbulent flows coupled with longer pumping time. When pulling out of the hole (POOH), the CT speed should be reduced to properly jet or stir the solids beds (with additional hydraulic power provided by the BHA) and place the particles in the flow stream while always keeping the highest flow rate possible. This way the undesirable short trips could potentially be eliminated while the operation remains safe and efficient.

It is convenient at this point to add comments on the CT pipe mechanics in the curvature. The accumulation of solids in the curvature also increases the possibility of high pulling drag in both moving directions and even the chances of getting stuck with the CT pipe or the BHA. Additionally, when the CT string and BHA are deeper in the horizontal well, the solids accumulation in the curvature can impair further penetration in the well. The main reason for this is that the curvature is where the forces are transmitted from the vertical section into the horizontal section: this happens because the helical buckling load is at its highest in the curvature, and this causes the pipe not to be bucked in the section, being laid in constant and close contact with the lower casing wall (unlike the pointy contact when buckled) for an extended length (Fig. 4). Therefore, additional mechanical friction caused by the presence of solids will reduce the force available to push pipe and BHA into the horizontal. This is another reason to use high turbulence during the job and minimize solids in the curvature while performing an operation at bottom of the well.

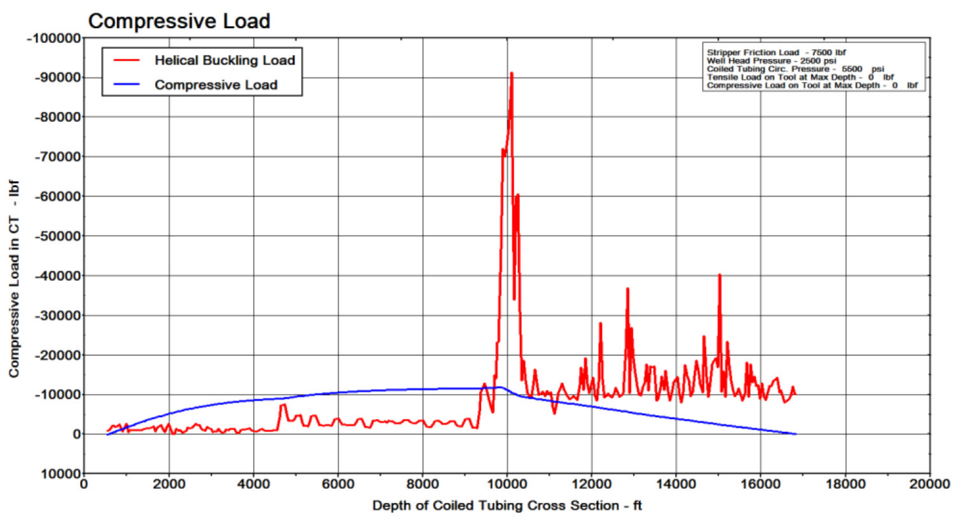

Figure 4—CT maximum compressive load.

It is important to observe that all concepts presented here are valid for any cleanout regardless of size of CT and tubulars, deviation, fluids, and environment. However, this discussion is solely focused in operations employing larger CT sizes, which offer the benefit of much higher fluid rates and velocities and Reynolds numbers that can exceed 60,000.

Before addressing rheological properties of fluids, it is worth discussing the process of short trips.

Fluid Sweeps and Short Trips

Gelled fluids are used in the vertical sections of horizontal wells or in vertical wells to reduce the settling velocity of particles. A similar approach is to pump gel pills or perform what is commonly known as gel sweeps. After milling a plug in a vertical well, pumping 5 bbl of a highly viscous fluid can help trap the debris and move particles towards the surface faster. Since the amount of debris is low, compared to proppant or fill cleanouts, it is not necessary to use a fully gelled system.

During plug milling in horizontal wells, a gel sweep is traditionally believed to help lift the solids and keep them in suspension. However, that is not the case in the horizontal section. A pill of gel will have more value in the vertical section. In the vertical section, the gel sweep can help to move some plug parts faster. Nevertheless, the used of fluid sweeps can increase the system viscosity since the fluids are recirculated. The changes in viscosity, as it will be explained in this paper, can do significant damage to the transportation of solids.

The term short trip out or short trip is a common term used in the CT industry when the CT string and BHA are partially pulled out of the hole during cleanout operations. In general, this trip starts in the deepest part of the horizontal section of the well and ends close to the vertical section of the well at deviations of approximately 20 to 30°. At these deviation angles, the well is believed to perform, for particle transportation and cleanout purposes, mostly as a vertical well. The main purpose of short trips is to help the removal of solids that are still present and slow-moving in the wellbore. As already pointed out, the solids distributed along the CT-completion annular gap are slowly removed by the shear effects of fluids. When fluid turbulence cannot be maximized due to a large wellbore size (in comparison to the CT string OD) or use of a nonsuitable fluid or when the amount of solids is fairly large, the improper transport of solids can be addressed by pulling the CT/BHA out of the hole. The jetting effect of the BHA picks up the particles from the lower side of the completion and immerses them into the fluid stream. As the overall transportation is not ideal, the POOH CT velocity must be low enough to allow the BHA hydraulic jetting effect to act as a sweep or similar to a ″squeegee″ effect. The worse the cleaning scenario, the more short trips and the slower these trips need to be to accomplish the task.

Although short trips have a fundamental value in the industry, improper use of short trips can bring a series of detrimental effects to the operation and to the operation economics. The first mistake is to believe that all cleanout operations need a short trip. If the milling and cleaning procedure is thoroughly planned, along with good fluids quality, short trips can be minimal or even eliminated in some instances. Short trips performed at higher CT pull-of-hole speeds do not maximize particle removal because annular velocity may decrease and swab the well. Although well swabbing should not be a safety or operational concern for any properly set CT operation, it is imperative to have, as a contingency, an adequate hydrocarbon separation system at the surface when this takes place. Additionally, the high-strength materials and somewhat weaker bias welds currently used in the current CT strings are not suitable to operate in a sour environment, which is common in several areas. This will increase the likelihood of H2S contact when the well is swabbed and, consequently, string failure. Another issue to be observed before engaging in short trips is the detrimental effects on CT pipe fatigue life. The shale market is dominated by expensive and relatively long strings with larger ODs, such as 2 in. and 2 3/8 in., which tend to fatigue rather quickly, incurring, in the process, substantial deformations, of which pipe ballooning is the main one. Ballooning, in particular, limits the future usability of the string and increases risks of getting stuck at the stripper and inhibiting the operation of the BOP sealing rams around the increased OD pipe in case of well control situation.

Table 1 documents the necessary additional pump rate to maintain constant annular velocity during a short trip performed at different POOH pipe velocities:

Table 1—Compensation rate to maintain AV constant with (2″ CT)

CT POOH Speeds (ft/min)	CT Pump Rate =	2.5 bpm
	Rate Variation (bpm)	AV Variation (ft/min)
0	0.00	226
10	0.04	223
20	0.08	219
30	0.12	216
40	0.16	212
50	0.19	209
60	0.23	205
70	0.27	202
80	0.31	198
90	0.35	195
100	0.39	191
110	0.43	188
120	0.47	184
130	0.51	181
140	0.54	177
150	0.58	174

The same practice of maintaining the annular velocity avoids creating a pressure drawdown to the formation (swabbing). It is important to note that this additional pump rate will increase CT pressure further exacerbating the negative effect of the short trip.

Table 2—Compensation rate due to 2 3/8-in. displacement.

CT RIH Speeds (ft/min)	CT Pump Rate = 3.5 bpm		Well Balance Level (choke determined) is =	0.2 bpm	Adjusted Surface Returns Rate in order to keep overbalance required of 0.2bpm
	Rate Variation (bpm)	Effective Rate (bpm)	Expected Surface Retuns Rate is =	3.3 bpm	
10	0.055	3.555	Overbalance - fluid squeezed in formation @	0.255 bpm	3.35 bpm
20	0.110	3.610	Overbalance - fluid squeezed in formation @	0.310 bpm	3.41 bpm
30	0.164	3.664	Overbalance - fluid squeezed in formation @	0.364 bpm	3.46 bpm
40	0.219	3.719	Overbalance - fluid squeezed in formation @	0.419 bpm	3.52 bpm
50	0.274	3.774	Overbalance - fluid squeezed in formation @	0.474 bpm	3.57 bpm
60	0.329	3.829	Overbalance - fluid squeezed in formation @	0.529 bpm	3.63 bpm
CT POOH Speeds (ft/min)	CT Pump Rate = 3.5 bpm		Well Balance Level (choke determined) is =	0.2 bpm	Adjusted Surface Returns Rate in order to keep overbalance required of 0.2bpm
	Rate Variation (bpm)	Effective Rate (bpm)	Expected Surface Retuns Rate is =	3.3 bpm	
10	0.055	3.445	Overbalance - fluid squeezed in formation @	0.145 bpm	3.25 bpm
20	0.110	3.390	Overbalance - fluid squeezed in formation @	0.090 bpm	3.19 bpm
30	0.164	3.336	Overbalance - fluid squeezed in formation @	0.036 bpm	3.14 bpm
40	0.219	3.281	Underbalance - Produced fluid - influx @	-0.019 bpm	3.08 bpm
50	0.274	3.226	Underbalance - Produced fluid - influx @	-0.074 bpm	3.03 bpm
60	0.329	3.171	Underbalance - Produced fluid - influx @	-0.129 bpm	2.97 bpm

Summarizing, short trips are an important tool for well cleanout efficiency and stuck pipe prevention, but the use of short trips must follow strict criteria and be part of a well-planned and executed operation.

Effects of Rheology on Cleanout Efficiency

In this section, we relate the main concepts of cleanout efficiency to field operations.

In practical terms, a fluid can be subjected to either a laminar or a turbulent regime, depending on the combination of the inertial forces and frictional forces. A convenient ratio in between these two forces, what actually determine its flow regime, is the known Reynolds number, Re:

$$\mathrm{Re} = \frac{\text{Inertial Force}}{\text{Viscous Force}}$$

or

Equation 1 - Reynolds number

Reynolds Number (Re)	Newtonian Fluids	Pseudoplastic - Power Law Fluids
CT Flow	$\mathrm{Re} = \frac{928\ \rho\ v\ D}{\mu}$	$\mathrm{Re} = \frac{1.86\ \rho\ (v)^{2-n'}\ (D)^{n'}}{(96)^{n'}\ k'\left[\frac{3n'+1}{4n'}\right]^{n'}}$
Annular Flow	$\mathrm{Re} = \frac{928\ \rho\ v\ De}{\mu}$	$\mathrm{Re} = \frac{2.28\ \rho\ (v)^{2-n'}\ (Do-Di)^{n'}}{(144)^{n'}\ k'\left[\frac{2n'+1}{3n'}\right]^{n'}}$

The Reynolds number is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces. Reynolds number is used to characterize different flow regimes, such as laminar or turbulent flow. Laminar flow occurs at low Reynolds number, where viscous forces are dominant, and is characterized by smooth, constant fluid motion, which leads to stability. On the other hand, turbulent flow occurs at high Reynolds number and is dominated by inertial forces, which tend to produce chaotic eddies, vortices, and other flow instabilities.

Mean Velocity Profiles for Turbulent Flow Near a solid, the completion pipe walls, for example, the flow has a different structure, called the boundary layer. The main characteristic of the boundary layer is that the fluid velocity goes to zero in the boundary layer, no matter how the flow regime is in the areas distant from the walls. This is known as the ″no-slip″ condition because the fluid sticks to the surface of the pipe in the boundary layer.

Turbulent boundary layers have a complex structure and a number of characteristic phenomena that are still not well understood, especially for high Reynolds number flows.

In laminar flow, the fluid molecules follow precisely the streamlines. This, plus the no-slip conditions at the boundary layer, renders the picking up and the transportation of particles lying on the lower side of the tubular very difficult. Short trips and a BHA with good hydraulics are fundamental in this scenario. If the Reynolds number is increased, turbulent eddies start to erupt in an erratic way. With further increase in the Reynolds number, the frequency and duration of the turbulent eddies also increase until the Reynolds number is high enough that a large number of turbulent eddies continuously erupt. The transition between laminar and turbulent regimes is also affected by the smoothness of the surface of the tubular. High surface roughness can bring turbulence at lower Reynolds number whereas smooth surfaces, which is the assumption in the scenarios covered in this paper, can prolong laminar flow to higher Reynolds number.

The size of the eddies can vary from very large, with the eddy crossing several stream lines, to much smaller. Eddies are superimposed on the main flow stream and reshape it. Fluid molecules follow the rotation pattern and receive correspondent momentum transfer from the eddies they are in contact with in that instance. The larger eddies occur more in the center of the flow stream whereas the smaller eddies are all over and close to the tubular walls in particular. If dye would be added to a laminar flow stream, only a filament of dye parallel to the stream flow would be seen (Fig. 5). In the case of turbulent regime, the same dye filament will follow the larger eddies and, when the dye comes in contact with the smaller eddies, it will diffuse. It is believed that solid particles, taking into account their different shapes and density, will suffer accelerations and change of directions in similar ways (MIT 2005).

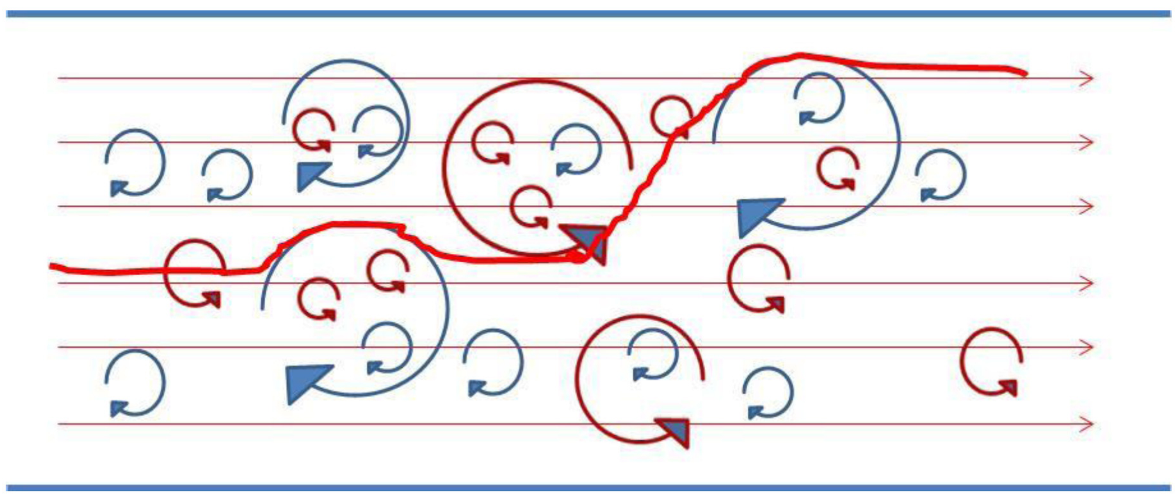

Figure 5—Turbulent flow and eddy behavior.

The viscosity or apparent viscosity of a fluid (more adequate for a power law fluid) is an important property in the analysis of liquid behavior and fluid motion near solid boundaries. Statistical modeling is continuously improved by the study of eddy arrangement and configuration, eddy structure of turbulent boundary layers, and surface eddy motion and interaction or surface eddies with the eddies on top of the boundary layer (Saldarriaga, 1998).

The profiles for completely developed laminar and turbulent flows are shown in Fig. 6.

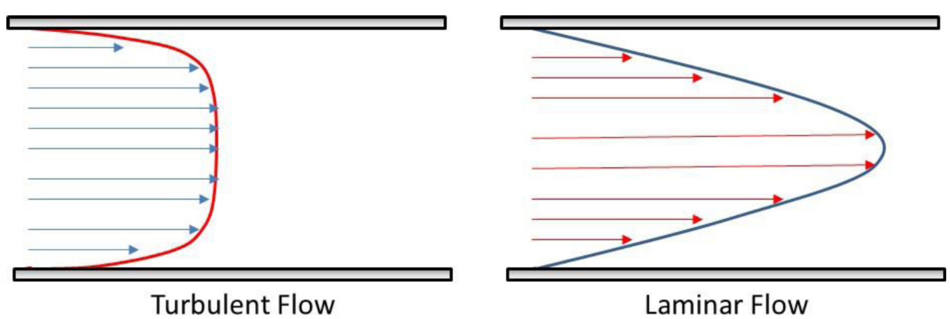

Figure 6—Velocity profile.

As it can be seen from the velocity profile in a pipe, turbulent flow transfers substantial moment from the center of the pipe to much closer to the walls. The higher mixing of fluid and transfer of momentum results in a much more flat profile in turbulent flow than in laminar flow. It is important to observe that in comparison to laminar flow, the velocities in a turbulent regime are substantially higher but also constant along the central region of the pipe. The size of the eddies decreases the closer to pipe walls. However, in the case of extreme Reynolds number, the velocity profile is very flat, and the number and size of the smaller eddies, the ones closer to the tubular walls, tend to increase, which benefits cleaning.

Turbulent eddies cause localized velocity fluctuations. As an example, the longitudinal (v) and vertical (u) velocity measured at a given point can vary over time due to turbulent fluctuations.

Vertical velocity in turbulent flow and velocity at any given point in turbulent flow are described by Eq. 2 and Eq. 3, respectively.

$$v(t) = v_{\text{average}} + v'(t) \tag{2}$$

$$u(t) = u_{\text{average}} + u'(t) \tag{3}$$

For a laminar flow regime when there is no velocity fluctuations over time:

$$u(t) = v_{\text{average}} = \text{Constant} \tag{4}$$

$$u(\text{t}) = u_{\text{average}} = \text{Constant} \tag{5}$$

As the turbulent fluctuations are random, the fluid molecules' movement can be characterized using a statistical approach. This brings another variable, the root mean square (RMS) of the velocity (V_{RMS}), which is, in reality, the standard deviation of the eddy's amplitude. Therefore, RMS is a measure of the scattering of velocities. The higher the V_{RMS}, the higher is the turbulence. It is important to observe that the average velocity can be localized, and the RMS velocity just measures the level of turbulence at that spot. Turbulence levels vary in both time and space in steady state. Fig. 7 shows the fluid eddy's velocity for both vertical and horizontal (x, y axes). Similar variations take place in the third dimension, the z axis.

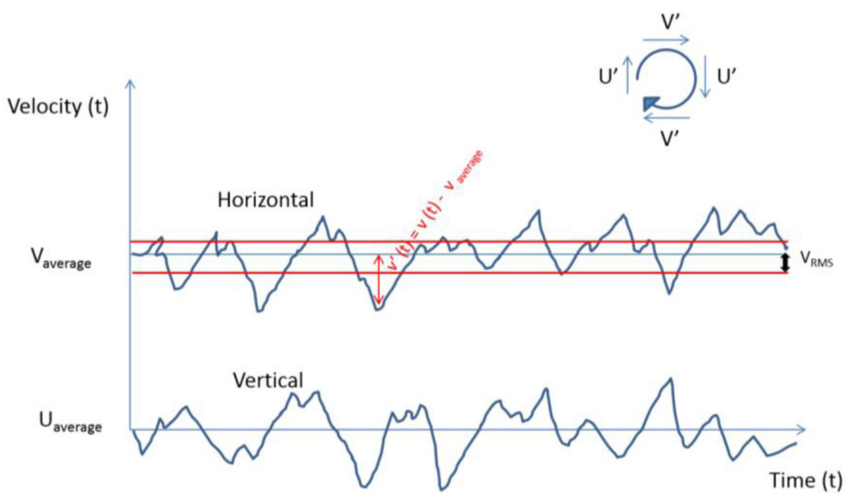

Figure 7—Fluid eddy velocity.

Near a solid boundary, such as on the tubular walls, the flow, even if in turbulent regime, has a different configuration called a ″boundary layer″. A boundary layer may be in laminar or in turbulent flow. In the boundary, independent or whether the fluid is flowing in a turbulent regime or not, a velocity gradient is established. The most important characteristic is that the velocity of the fluid decreases to zero. This is the no-slip condition already discussed. It is a consequence of viscosity. If a zero-viscosity fluid could be developed, the no-slip condition would not be true, but this does not exist. As can be seen in Fig. 8, there is a velocity profile across the boundary layer from surface to free-stream velocity, which is reached asymptotically, that characterizes the end of the boundary layer. This velocity profile over a distance is, in reality, shear. This specific shear rate is known as the momentum boundary layer.

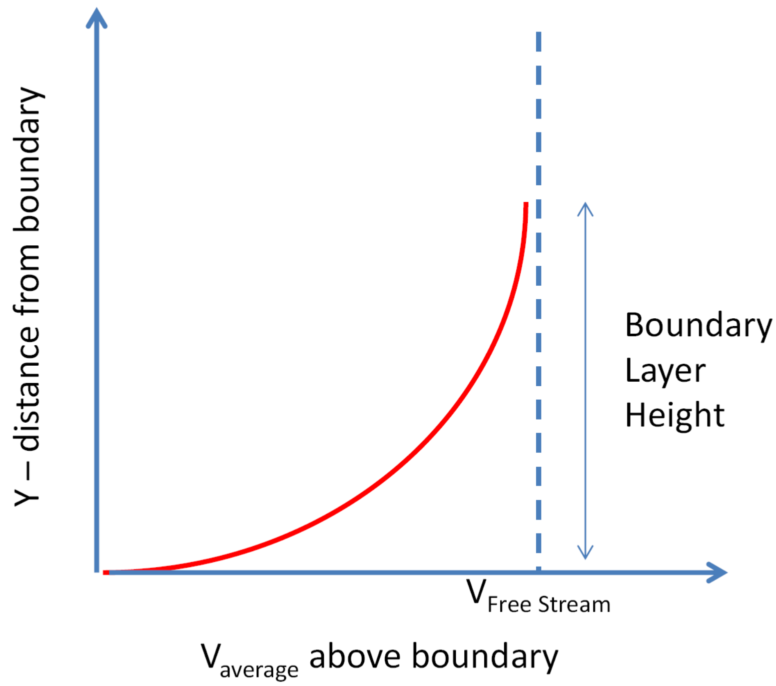

Figure 8—Average velocity above boundary.

As already pointed out, the boundary layer can be laminar or turbulent. The above graph can be plotted for the different velocity profiles across the boundary is:

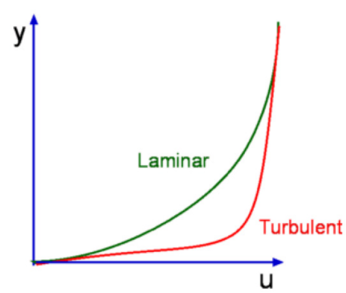

Figure 9—Average velocity above a boundary for laminar and turbulent flow regime. In a turbulent boundary, there is a very steep gradient of velocity. This corresponds to a high shear rate and high shear stress.

This means that even within the boundary layer, the fluid velocities are much greater close to the wall surface in turbulent flow than in laminar flow. Naturally, the complexity of the boundary layer goes beyond this discussion and involves the laminar sublayer, but it is important to observe that the boundary layer is dynamic and changes with turbulence levels: the higher the level of turbulence and Reynolds number, the thinner the layer gets, and momentum can be increasingly applied to the particles, putting them vigorously back into fluid stream as they hit lower tubular walls. The thickness of the boundary layer becomes compatible with the particle size, and the fluid constantly transports the particles with an improved sweeping ability. In the case of flat particles, such as carbon fiber skin from drillable isolation plugs, their shapes and constant particle rotation makes them travel to the surface at lower speeds, but their movement is still constant. On the other hand, larger and heavier particles will also travel at lower speeds, and the challenge is more in the curvature and vertical sections of the well.

How Roughness Affects Flow Patterns

The roughness of tubular surfaces affects flow patterns and its characteristics. Roughness can accelerate the start of turbulent flow, but this is of less interest to this discussion. As a turbulent profile develops further, smoother surfaces cause quicker flattening of the velocity profile, which is a better profile for particles transportation (Fig. 10).

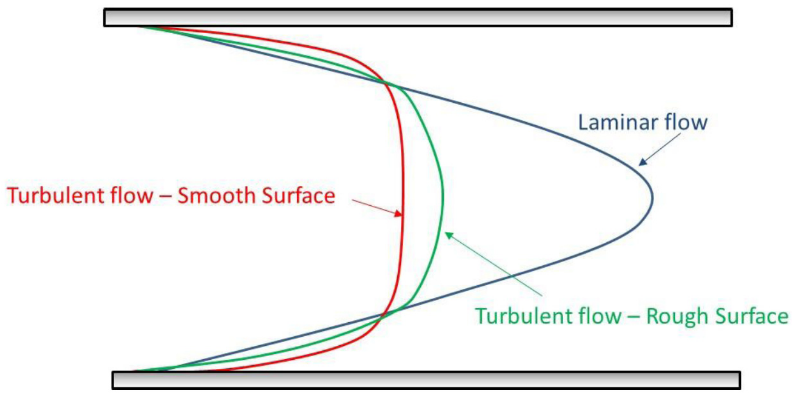

Figure 10—Velocity profile.

Another important aspect of roughness is fluid friction pressure, but this has little relevance in this discussion.

Summary of the Key Parameters

The discussions above help to determine key cleanout parameters. These key parameters are important for benchmarking as they allow a better analysis of the performance of cleanout operations completed in wells that share similarities but are hardly identical.

The parameters that govern a well cleanout fall into the categories of overall well parameters, fluids and equipment, and procedures:

- Well Parameters:
  - Well and Coiled tubing
  - Completion/casing ID
  - Lateral length
  - Lateral deviation and toe (up or down)
  - Type of fracturing isolation plugs
  - Number of isolation plugs set in completion
- Fluids and equipment
  - Type of fluids
  - Friction reducer type and concentration
  - Fluid viscosity
  - Lubricant type and concentration
  - Additives mixed and homogenization
  - Coiled tubing string
  - CT OD
  - CT string length
  - CT material strength
  - Flow Back

- Particles strainer
- Bottom hole assembly
- BHA
    - Size and components of BHA
    - Size of downhole motor
    - Type of bit or mill being used
- Procedures
    - CT run in hole (RIH) speeds
    - POOH speeds
    - Short trips
    - Short trip CT speeds (in and out)
    - Short trip initial and final depth
    - Full elimination of short trips (continuous cleanout)
    - RIH speeds in between plugs
    - Fluid pump rates
    - Flow back rates - Barrels in versus Barrels out (underbalance/ overbalance levels)
    - Plug milling
    - Type of motor and mill combination
    - Differential pressure applied to mill plugs (weight-on-bit)
    - Time to mill plug
    - Amount of solids recovered over time and per plug

Field Tests

The path to improve cleanout work performed in shale wells involved several field steps planned on an incremental basis. The ultimate goal was to maximize cleanout efficiency, eliminating viscous pills as well as wiper trips and short trips.

The implementation of plug milling without the use of viscous pills is the result of several enhancements made to the plug milling application in high-pressure wells. The performance during plug milling does not rely on one variable only, and there is no magic formula that can be successfully applied to every field and scenario. Each CT intervention requires a detailed analysis and design process to increase the chances of success during the intervention. Given the similarity of the wells in the mass production shale market, it could be valid to apply certain practices in the same field once the design process is done and defined for that particular set of wells.

There were three phases in the trial.

Phase 1 was the pre-trial phase. In this phase, several changes were implemented in a continuous improvement process, culminating in the elimination of short trips.

Phase 2 was the trial itself. In this phase, the focus was on the use of non-gelled fluids. Preparation and quality of fluids throughout operations were continuously monitored and corrected as needed and the effect of the fluids were carefully measured and evaluated. The most important outcome of this phase was the full understanding of the importance of fluid consistency and adherence to improved cleanout procedures.

Phase 3 is the post-trial phase. In this phase, there was wide-scale implementation of the non-gelled system and the improved procedures in the field for all plug milling operations.

Before the final step of eliminating viscous pills from the operation, several adjustments to plug milling procedures were made in phase 1. To explain the field results, it is necessary to make a summary of key changes in the process.

Plug Debris Transport Mechanism and the Importance of Fluid Velocity and Pipe Speed

As has been discussed in this paper, for low rates and low-viscosity fluids, the mechanism of transportation of the plug parts in the horizontal section is not suspension. The mechanism is saltation, that is, the rolling of solids particles (Leising and Walton 2002).

The solids velocity that is achieved by this mechanism is lower compared to the speed achieved by suspension of solids. In the build-up section, the solids movement is slower due to the tendency of the bed to become unstable as it accumulates solids. When the bed is unstable, the debris will slide downwards (Li and Walker 1999). Therefore, even with the right fluid, the times for solids removal are longer than expected or estimated with the conventional annular velocity calculation. In the lateral section, the CT speed between plugs needed adjustment. To increase the chances that debris would be moved through the lateral consistently if larger accumulations were encountered while tripping in the hole, the CT speed was reduced to allow nozzle hydraulics to act on the accumulations, diluting the solids into the flow stream. On the other hand, as stated previously, the tripping speed affects the annular velocity. Higher in-hole speeds result in higher annular velocities. At the higher Reynolds number obtained with a non-gelled fluid system, there is a possibility that these solids accumulations found while tripping in hole are removed even without the aid of bit hydraulics. Therefore, a next step that remains to be tested is to increase tripping-in-hole speed while observing hole cleanliness.

The CT speed was reduced during the optimization process. It was reduced between plugs while milling and while POOH in wiper trips, and it was significantly reduced in the buildup section in the final trip. The speed was reduced even more in the buildup section to permit the movement of the CT to break any dune and put debris from the plug part back into the main liquid stream. This adjustment to the speed did improve the efficiency of the milling operation; the result was more plug debris recovered at surface and the elimination of wiper trips, with the POOH trip the only wiper trip taking place in the whole operation.

However, further changes needed to be done to achieve a significant amount of solids at surface while keeping the operation within a reasonable time span. Speed can only be reduced to a certain point before it affects the economics of the operation.

Dosage of Chemical Additives

With the water constraints in the current US land milling operation, it makes a lot of sense to use recirculation as a mean of optimizing the amount of water required to clean a horizontal well. The long laterals and high pressure also demand the use of additives to reduce fluid and metal-to-metal mechanical friction. Nevertheless, when the fluids' turbulent flow plays such a role in the transportation of solids, changes in viscosity are very detrimental.

Using the Reynolds number criteria, it is possible to measure the level of turbulence during the cleanout. As it has been stated in different studies, the viscosity has an inversely proportional effect on the Reynolds number. The higher the viscosity, the lower is the Reynolds number and the higher is the critical velocity needed to avoid the stationary bed formation.

Friction reducers will perform optimally at specific concentrations. If the friction reducer continues to be added to the system, it will only increase viscosity without reducing the friction pressure. Furthermore, the rise in viscosity can be so high that will not only reduce the Reynolds number, but it will also increase the friction pressure. If we could plot drag reduction versus friction reduction concentration, we could see a parabolic behavior with a flat peak.

To determine the impact of friction reducer overdose, we run friction loop tests. In these tests, it was possible to determine the ideal concentration for maximum fluid drag reduction. It was also possible to evaluate and quantify the increase in viscosity if friction reducer continues to be added to the system. Fig. 11 and Tables 3, 4, and 5 summarize the results of these tests.

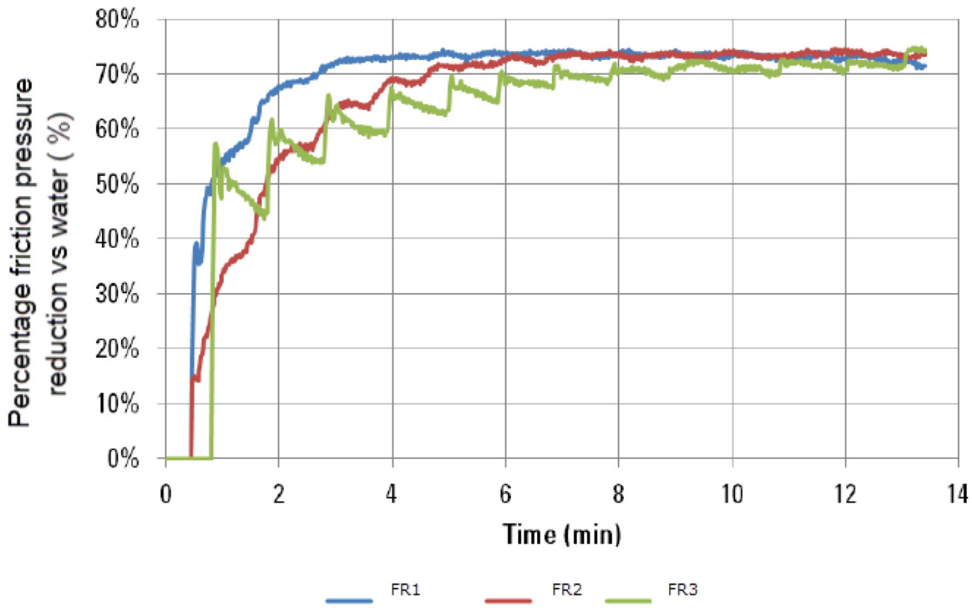

Figure 11—Friction loop test with various friction reducers at different concentration.

Table 3—Concentration and viscosity for maximum drag reduction for different friction reducers (FR).

	FR1		FR2		FR3	
Concentration for maximum fluid drag reduction vs water	0.3	GPT	0.6	GPT	0.8	GPT
Viscosity at 511 (1/s)	4.5	cp	5	cp	4	cp
Viscosity at 1021 (1/s)	4	cp	4.5	cp	3.5	cp

Table 4—Viscosity at 2 GPT (gallon per thousand) for all three friction reducers.

	FR1		FR2		FR3	
Overdose of FR	2	GPT	2	GPT	2	GPT
Viscosity at 511 (1/s)	7	cp	6	cp	5	cp
Viscosity at 1021 (1/s)	5.5	cp	5	cp	4.5	cp

Table 5—Percentage increase in viscosity due to excess of friction reducer.

		FR1	FR2	FR3
Viscosity increased from that at max	511 (1/s)	55.56%	20.00%	25.00%
Viscosity increased from that at max	1021 (1/s)	37.50%	11.11%	28.57%

It is possible to observe in Fig. 11 that after 3 minutes, adding friction reducer has no effect on the percentage of drag reduction. If more friction reducer is added, drag will eventually start to increase.

Knowing such variations in viscosity, makes possible a sensitivity analysis of the Reynolds number by plotting the Reynolds number as a dimensional variable dependent on rate and viscosity. The results of this analysis are presented in Fig. 12 and Fig. 13.

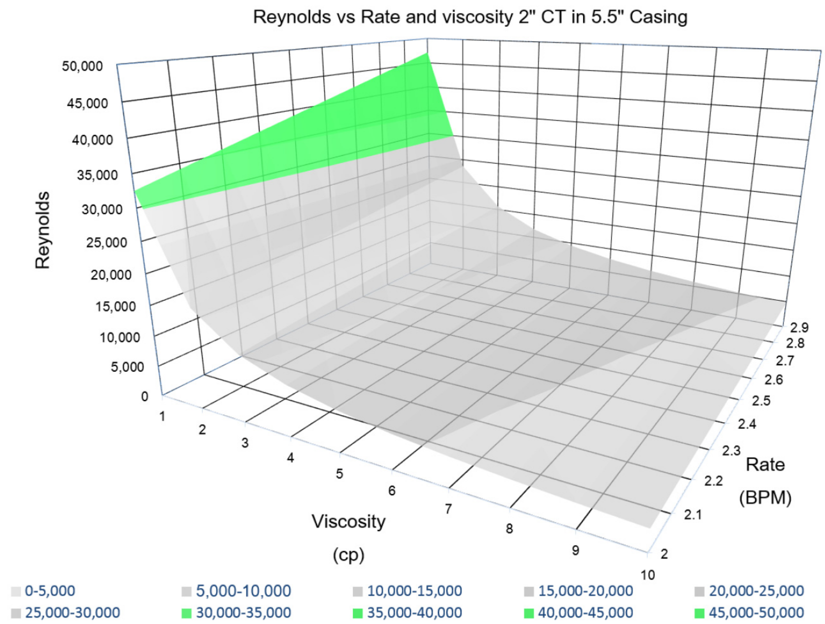

Figure 12—Reynolds number vs. viscosity and rate in 2-in. CT and 5.5-in. casing-annular space.

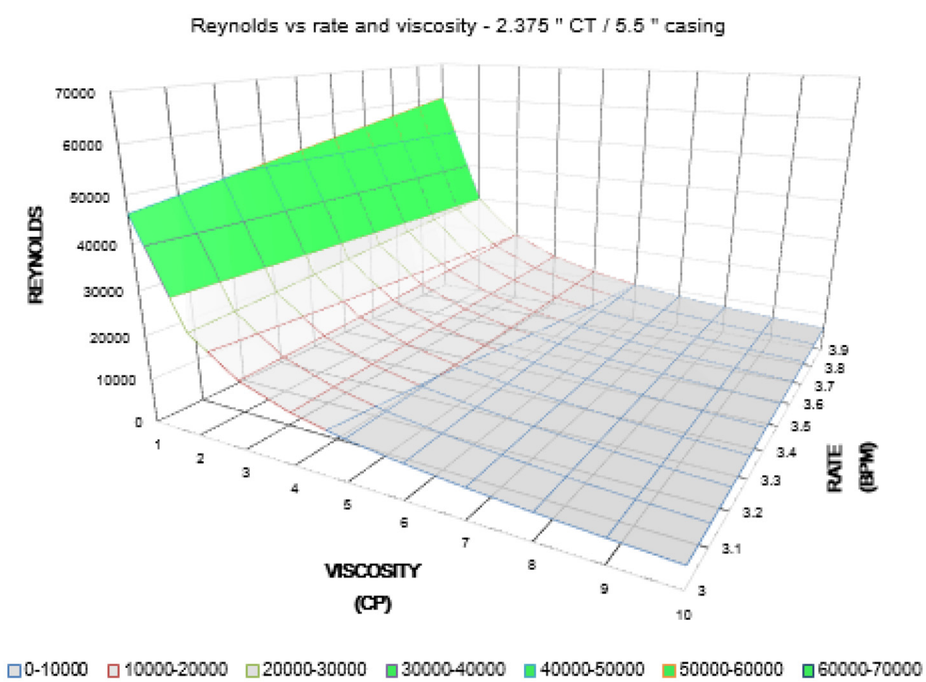

Figure 13—Reynolds number vs. viscosity and rate in 2 3/8-in. CT and 5.5-in. casing-annular space.

During the trial, it was observed that the range of Reynolds numbers that gave better results is from 50,000 to 70,000. What can be concluded from the laboratory test and Reynolds measurements, is that the window of optimum performance is not large. The surface plot in Fig. 12 shows the range of Reynolds number at different rates and viscosity for a typical 2-in. CT drillout. If all conditions are ideal, we can achieve a good Reynolds of 35,000 to 50,000. This area is plotted in green in Fig. 12, and Is only applicable in a narrow 1-cP viscosity range.

Fig. 13 the same plot as in Fig. 12, but for 2 3/8-in. CT. It can be observed that changes of 1 or 2 cP can make the Reynolds number drop significantly, from 53,000 to 26,000 (see Table 6, the Reynolds number matrix). What this change means is that, even with 2 3/8-in.CT, the turbulence can go down as much as with 2-in. CT with a mere drop of 1 cP. An interesting observation is that the impact of the viscosity is greater than the impact of the fluid rate. The rate can be dropped by half a barrel per minute, and it will not cause as many problems as allowing the liquid system to go up 1 or 2 cP. For 1 cP at 3 bbl/min, the Reynolds number is still above 45,000. At 2 cP at 3.8 bbl/min, the Reynolds number remains below 30,000. Rate of 3.8 bbl/min in 5.5-in. casing can suggest a great annular velocity and good solids transport, but the truth is that the high rate and large diameter will not be effective unless the viscosity is controlled.

Table 6—Reynolds number vs. viscosity and pump rate for 2 3/8-in. CT in 5.5-in. casing.

		Rate (BPM)									
		3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9
Viscosity (Cp)	1	46174	47713	49252	50791	52330	53869	55408	56948	58487	60026
	2	23087	23856	24626	25396	26165	26935	27704	28474	29243	30013
	3	15391	15904	16417	16930	17443	17956	18469	18983	19496	20009
	4	11543	11928	12313	12698	13083	13467	13852	14237	14622	15006
	5	9235	9543	9850	10158	10466	10774	11082	11390	11697	12005
	6	7696	7952	8209	8465	8722	8978	9235	9491	9748	10004
	7	6596	6816	7036	7256	7476	7696	7915	8135	8355	8575
	8	5772	5964	6156	6349	6541	6734	6926	7118	7311	7503
	9	5130	5301	5472	5643	5814	5985	6156	6328	6499	6670
	10	4617	4771	4925	5079	5233	5387	5541	5695	5849	6003

Therefore, when viscous pills and any other type of viscous additives are added to the system and recirculated in the well, the transportation of solids is negatively affected. Attempting to improve the fluid rheology by chemical dosage was implemented at certain stages before eliminating the use of gel. The overall result was a better solids movement in the horizontal as well as in the buildup sections and the elimination of wiper trips.

Larger CT

There are several challenges when using a larger pipe for plug milling in high-pressure wells. Those challenges are not within the scope of this paper, but is important to mention that a larger pipe will fatigue and deform faster in such conditions. Consequently, the economics and limitations of such changes must be studied in detail before taking such step. On the other hand, there are significant benefits.

With the introduction of a larger OD pipe, it was possible to increase the annular velocity and, as consequence, the fluid turbulence. This change also allowed the use of larger downhole motors, which reduced the number of stalls and made milling rather comfortable compared to the struggle of milling with smaller downhole motors. The motor stalls during milling exacerbate pipe fatigue usage due to the pressure spike as well as the required string cycle to bring motor back to milling conditions. The focus shifted from going through the plug as fast as possible to milling down the plug parts.

Field Results

For the purpose of this paper, 13 jobs were chosen and analyzed (Phase 1 and Phase 2). All jobs were executed in the Eagle Ford under the same field conditions and following the same procedures. The method was fixed to ensure consistency in the execution. Occasional variations in pipe speed and weight on bit are hard to control and could affect the outcome of the experiment.

The last seven jobs, phase 2, were executed following the same procedure except that viscous pills were not allowed at any point during the job. There was also a careful dosage of chemicals to avoid an increase in the fluid system viscosity due to the recirculation of additives. All the jobs have the common denominator of following improved procedures and better hardware configuration, such as a downhole motor and mill combination.

Despite all the improvements, the results when using just fresh water were better than the results when viscous pills were pumped. The average amount of plug parts recovered on those jobs performed without gel was 4 lbm per plug. The quantity of average plug parts recovered in those jobs with viscous pills was 2.1 lbm per plug.

In Fig. 14 summarizes the results in terms of quantity of plug parts. Fig. 15 relates quantity of plug parts to speed, and Fig. 16 shows the other parameters monitored during the field test.

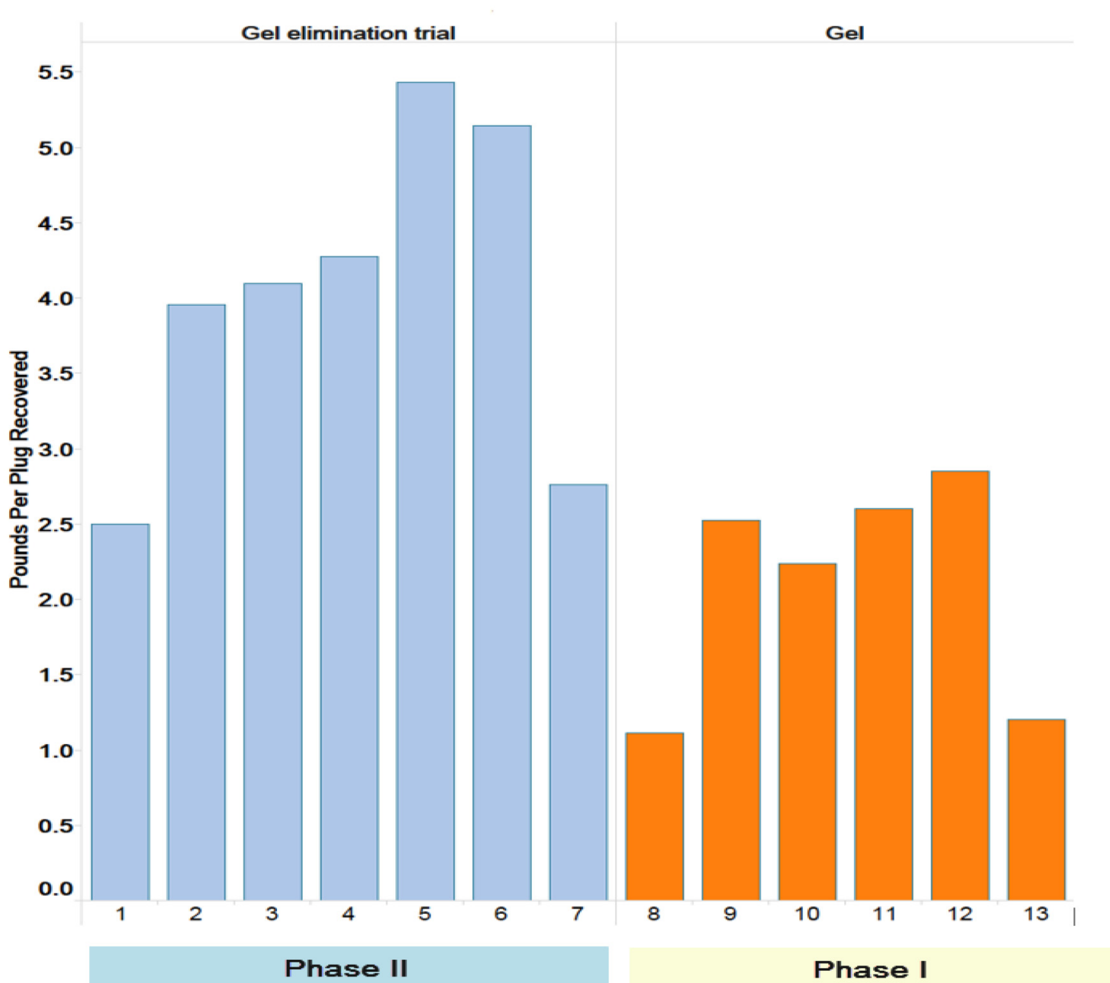

Figure 14—Pounds per plug recovered at surface.

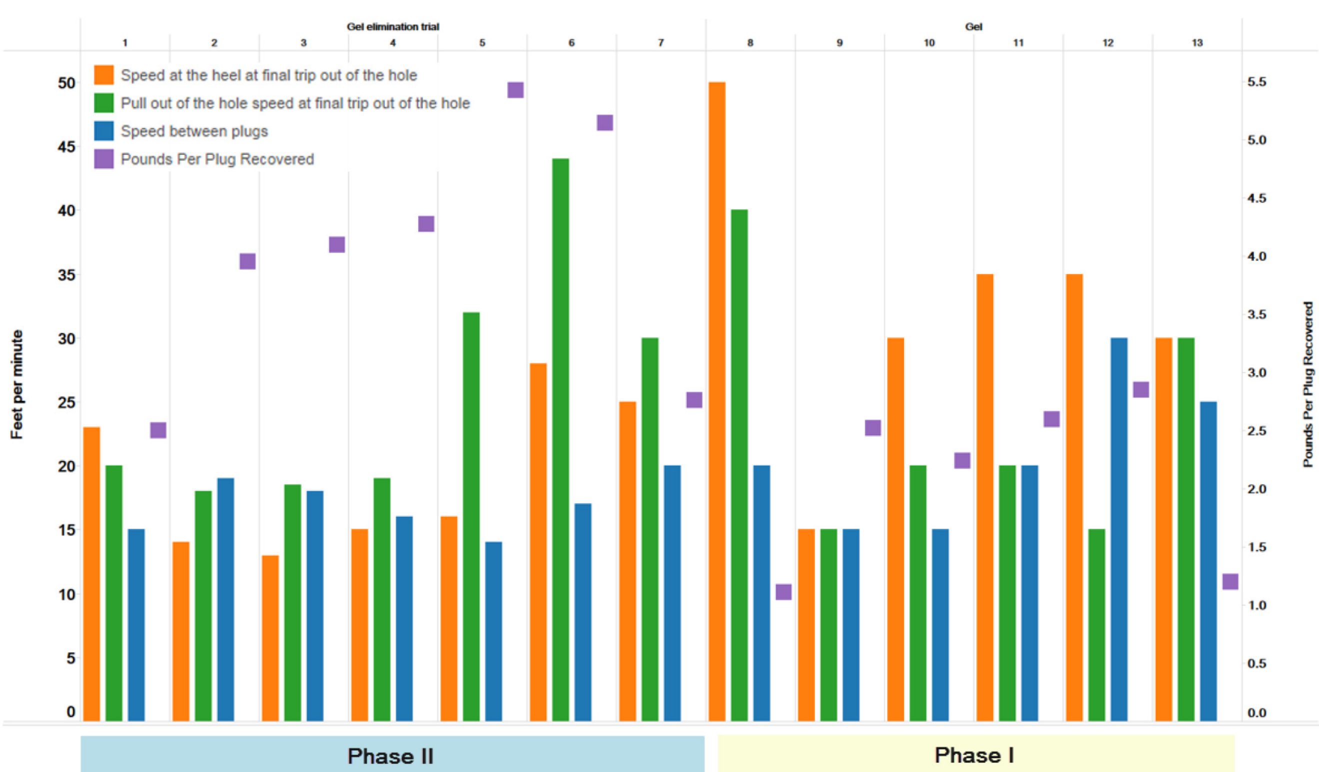

Figure 15—Speed at different stages of the clean out vs. pounds of per plug recovered.

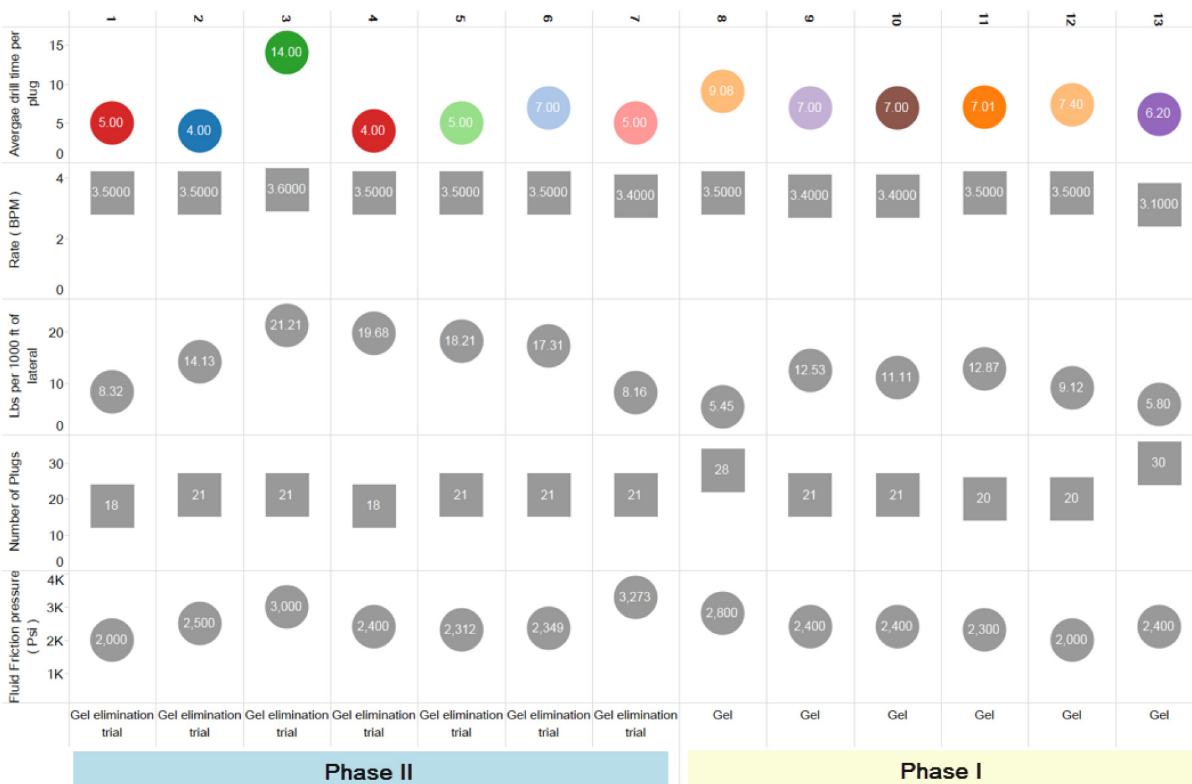

Figure 16—Additional parameters monitored during the field trial

Those jobs performed without viscous pills did not necessarily have homogenous rheology. Even if the additives concentration is controlled, the viscosity will vary. Variations in the Reynolds numbers were also observed in those jobs performed without viscous pills. The changes are due not only to variations in viscosity but also fluctuations in the rate. It was observed that the wells with a constant low viscosity and high Reynolds numbers had more solids arriving at surface while running in hole, compared to the ones with higher Reynolds numbers.

With the right speed, a wiper trip is very effective and can help dislodge the dunes from the casing walls and move them towards the heel. Then again, it is the capacity to move solids in the lateral while RIH that is largely dependent on the turbulence of the flow. If plug parts are not effectively moved while RIH, they will form beds that will not allow the free movement of the pipe.

The best example was observed during the field test in job number 6, illustrated in Fig. 17. In this job, 21 plugs were milled, and 5.4 lbm per plug were recovered. The relevant characteristic of this job is that the majority of the plug parts and solids were recovered while milling all plugs, in other words, while RIH.

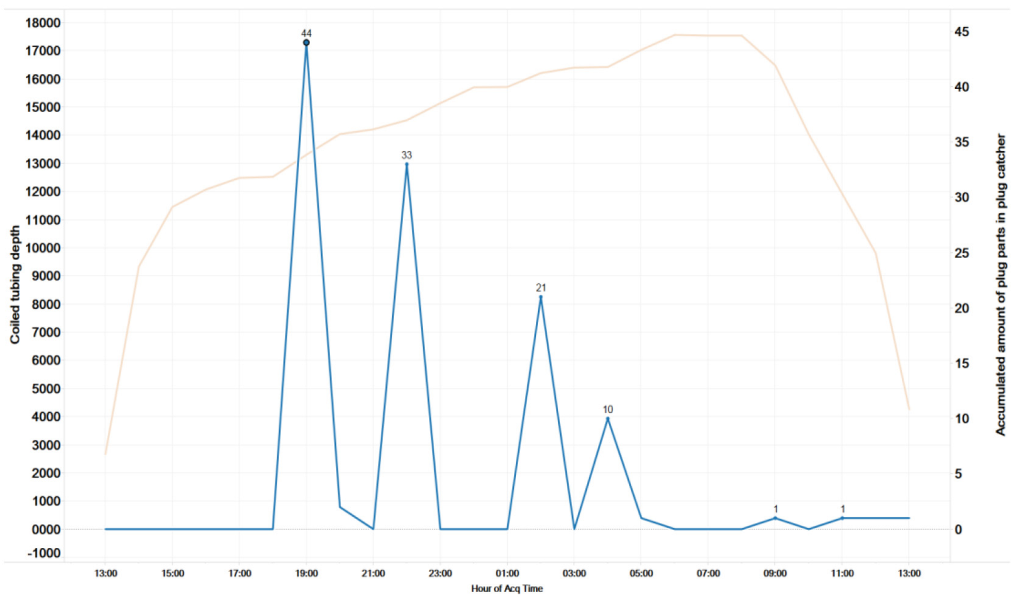

Figure 17—Job 6 accumulative plug parts at plug catcher vs. CT depth

How much plug debris is recoverable? It could be argued that the data suggest an unsuccessful cleanout operation and wiper trip since the weight of a plug can be close to 25 lbm compared to the 5.4 lbm recovered. Yard tests performed in a controlled environment indicate that this amount of plug parts is within the expectancy for the type of plug that was run in this well:

During the drill-out optimization process, BHA configurations were yard tested in a controlled environment, via the utilization of a closed pump loop, to obtain the best downhole-motor-and-bit configuration. Even under this controlled environment, only 5 to 7 lbm of plugs were recovered. Some parts disintegrate and dissolve. Hence, they are not big enough to be trapped in plug catchers or standard screens. Based on these tests, it is fair to call a job successful when 4 to 6 lbm of plug parts are recovered at surface.

Field Test Discussion and Post-Test Implementation

Given the positive results of the field tests, plug-milling procedures without the use of viscous pills were implemented for 23 subsequent field jobs after the trial. To which we have referred to as Phase 3

Although the type of well remains very similar, the results of phase 3 were difficult to compare with phase 1 and phase 2 wells simply because of changes in the methodology to capture plug parts and the fact that proper dosage was not present. Our conclusion is that the apparent reduction of plug part debris recovered is the result of bigger screens and the lack of proper dosage. In addition to that, adherence to proper practices and procedures is not easy to control in real-world operations that are not part of a field test. The summary of all three phases is presented in Fig. 18 and Fig. 19.

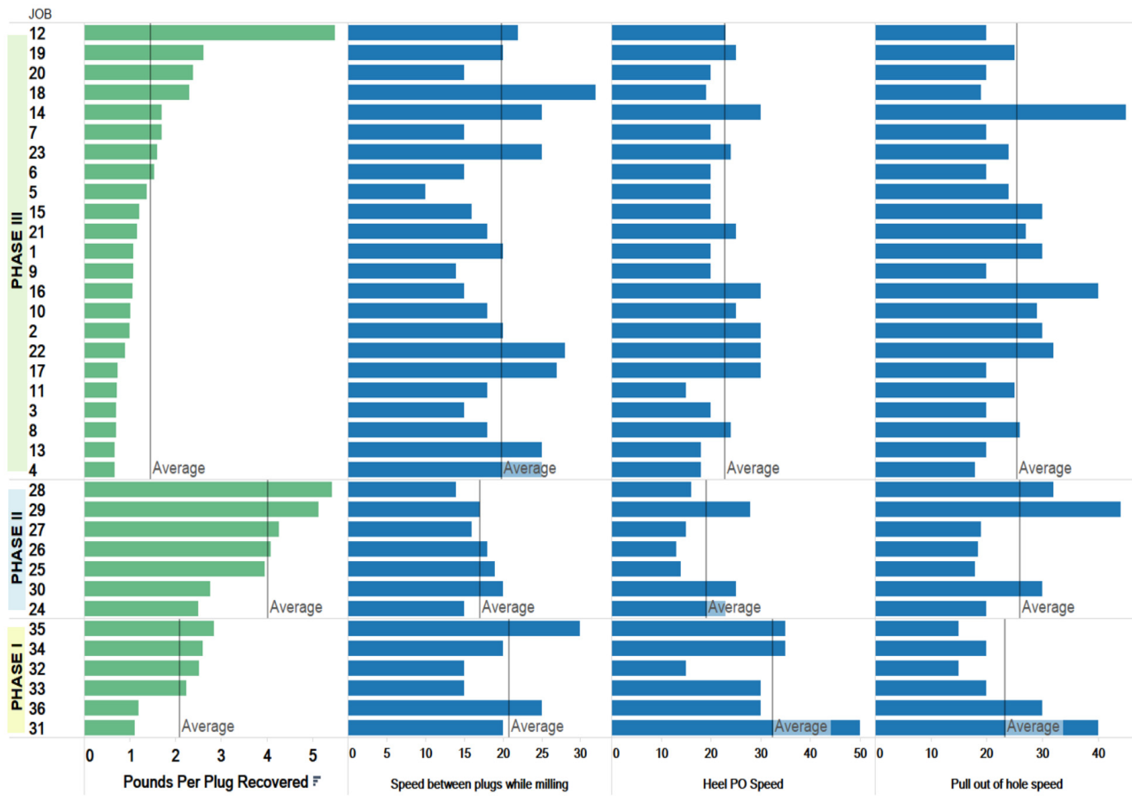

Figure 18—Summary of speed for all three phases.

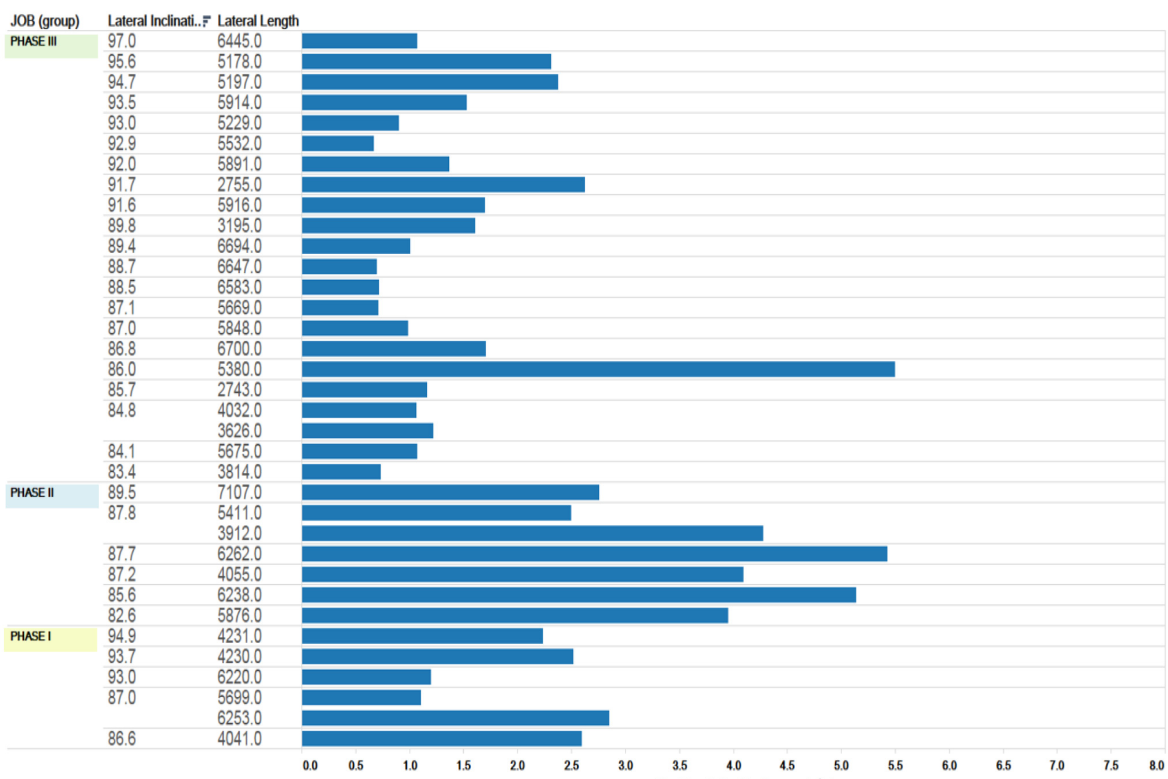

Figure 19—Summary of additional parameters for all three phases.

Yet, some wells in the post-trial phase serve to prove the concept in giving very positive results, and this encouraged a consistent implementation of non-gel drill-outs. Although the amounts of plug parts recovered in the jobs after the trial are not as good as the field test, it does not mean that all progress is lost. Those jobs remain efficient, with no short trips and no stuck events. In any case, the lack of adherence to design and proper procedures will slowly reduce the efficiency and will, eventually, generate nonproductive time.

The intention of this paper is to encourage two best practices among operators and service companies: the application of proper engineering design for CT interventions and consideration of the guidelines for fluid viscosity and flow in horizontal and buildup sections.

Proper engineering design for CT interventions is essential. Whereas horizontal drilling, fracturing, and completion techniques, and planning have consistently evolved and have become the main driving forces in efficiency gains and cost reductions during the shale boom, CT plug drill-out and wellbore cleanouts seem to rely still on old techniques developed for vertical wells, such as heavy viscous pills.

The CT industry, like any other, needs to evolve by replacing some deeply rooted techniques with newer, more efficient methods and prove its efficiency and reliability by the use of better-engineered practices. The exercise to improve the effectiveness of plug milling led to significant reductions in cost and time. In addition to the savings in the well construction phase, starting over with fewer solids accumulated in the wellbore will lead to better productivity and longevity prior to the first workover in the well. In addition, when the workover takes place, prepare for solids to be accumulated or sliding back and forth over the buildup section.

Efficiency is the ability to obtain repeatedly good results and improve them in a sustainable and continuous manner. In this paper, we advocate also for effectiveness and the application of engineered practices. It does not matter if we master a task to be done faster and faster if the task itself is not the correct one to achieve our goals. Effectiness and efficiency need to work together to build an increasingly competitive CT industry.

The second lesson learned is the advantage of using low-viscosity fluids and highly turbulent flow in the horizontal section and the importance of addressing the buildup section in particular. Viscous fluids and a pill can be the best option to transport particles in the vertical section. It can also help to keep in suspension solid particles in the lateral for longer horizontal lengths. However, when the particles fall in the casing wall again, the viscous fluid will not contribute to lift the particles again, and dunes will unavoidably form again.

Using a few high-viscosity pills might not be critical and can assist in the vertical section, but the combination of recirculated viscous pills and additives affects the whole system. If the viscous pills could be isolated (i.e., being pumped as a slug only), the effects could be less harmful than when the full viscous system is being recirculated.

Fluid selection is just one variable in the process; the exclusion of heavy viscous pills alone cannot overcome flaws in procedures or BHA selection. Therefore, it is recommended to change not only to fresh water in horizontal wells for milling applications, but also look in detail the rest of the parameters for a proper design. Reynolds number calculations can help to measure the current turbulent flow and to compare results when changes are made. Inexpensive field techniques can be adapted and utilized to measure fluid characteristics on the job.

Summary and Conclusions

The non-gelled fluids project has shown that substantial gains in both time and costs can be realized when viscous fluids and pads are replaced by a single fluid with low rheology with the capability to develop the highest possible Reynolds number. Turbulence levels are relatively easy to attain with the large pipes and somewhat viscous fluids but, as observed in the project, the levels of fluid turbulence that provide superior efficiency are several times greater in magnitude. Particles lifted and transported by low- rheology and high-turbulence fluids do not suffer the effects of gravity and settling but rather strike walls and other surrounding particles and are violently decelerated at a very high rate but are almost immediately picked up and accelerated again with the same vigor. This is the closest to full suspension that one can get. On the other hand, viscous fluids, at much lower turbulence levels, do carry particles for longer distances, but cannot pick up a particle and accelerate it back once it has struck a wall. This is when short trips/wiper trips are done to use the energy of tool jetting to put particles back onto fluid stream and accompany the particles all the way to the more vertical sections of the well.

However, as already repeatedly mentioned in this discussion, a successful cleaning operation is a combination of procedures and tools/fluids for a given scenario. Failure to obtain this optimum combination leads to highly unsatisfactory results. This was experienced in the post-trial, or commercial, phase of this project. Wells with similar characteristics to the trial wells had results far below expectation because the procedures from the field trial were not fully implemented and fluid properties were not controlled. This brings the important topic of the crew's awareness and training, both from operators and service companies. The implementation of new technologies and techniques ideally should be preceded by formal communication and training. Proper engineering design and preparation must be fully matched by field personnel commitment and skills to follow recommended procedures and be able to apply correct contingency and adjustment steps during the operation to fulfill original cleanout goals.

Although CT core activity is directly related to workover and production, in the shale market, CT service is directly associated with drilling activity and has a different competitor's profile. Although the learning exposed in this paper is valid for both scenarios, the CT industry in the shale market must continue to keep its competitiveness against competing completion technologies by increasing reliability and efficiency. With this in mind, CT can still be the most cost effective and competitive technology in the market.

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