Nine

A Viable Solution for Plug Mill-out Operational Challenges

An In-depth Look at Overcoming +13,000-foot Laterals with 2.375-inch Coiled Tubing

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SUMMARY

Extended well laterals, high-intensity proppant loadings, and the use of slick water fluids for hydraulic fracturing are three recent developments in North American unconventional shale plays that are supported by the shift toward improved well designs. In an effort to maximize well productivity and economics, operators continue to stretch the boundaries of well laterals from 10,000-ft to over 15,000-ft. These super lateral wells create substantial problems and push the limits of extended-reach coiled tubing (CT) operations. The operational field specifics, string designs, and downhole tool considerations that have the largest impact on the performance of extended-reach interventions in super laterals with 2.375-in CT are described in this publication.

The majority of U.S.-based operators have experienced wide success using CT for post-fracture plug mill-out and cleanout operations with laterals in the 7,500 to 10,000-ft range. Larger CT diameters and higher pumping rates are necessary for these well designs in order to successfully achieve work objectives. To access target depths, 2.375-in CT diameters over +23,000-ft in length with optimal wall thickness designs and materials are typically used. The CT performance in these super lateral wells was evaluated using friction matching of operational plans comparing CT forces, lockup behavior, and hydraulics analysis. Utilizing CT in these intricate wells must also take into account other operational aspects including equipment accessibility, logistical concerns, and field deployment.

Field results showed that employing specialized designed 2.375-in CT along with extended reach tools (ERT), chemical additives, and specialized operating techniques that increase efficiency, CT well interventions in over 14,500-ft laterals are viable. In order to enhance lateral reach capabilities and service life in extended reach operations, high-strength, quench and tempered material with specialized wall configurations and the most recent taper technology are used. In addition to optimized string designs, the newest technology in ERTs and fluid additives is critical while operating at over 7,000-psi pump pressure and four barrels per minute (BPM) circulating rates.

These records set by the industry show that there is still more room for longer laterals. To conduct safe extended lateral completions on a wider scale, cutting-edge technological advancements in surface equipment, downhole tools, CT materials, highly engineered string combinations, and sophisticated operational techniques and logistics are needed.

INTRODUCTION

The exponential rise in oil and gas output over the past few years has been fueled by recent advancements in hydraulic fracturing and horizontal drilling, which revived interest in unconventional reservoirs. These innovations made it possible to produce shale oil and gas for less money while also enhancing profit margins as the wells reached higher production rates.

Operators increase reservoir contact while reducing surface footprint by drilling longer lateral lengths to maximize well production and profitability. Even though 10,000-ft laterals are most common, well producers continue to push the lateral limits to over 15,000-ft. These wells exhibit difficulties in all aspects of the well construction but are particularly challenging for CT interventions.

LENGTHY LATERALS ARE STEADILY ON THE RISE

By the end of 2019, wells with laterals longer than 23,000-ft had been drilled all over the world. The Utica Shale formation's record well lateral in North America is over 19,000-ft long (Oil and Gas 360, 2018). Super laterals have many benefits and efficiencies, but because of their complex trajectories, these wells make service operations more difficult for the duration of a well's life.

Since 2013, there has been a noticeable increase in the percentage of drilled wells with laterals longer than 10,000-ft, according to a summary of data from drilling records. By the end of 2019, a third of all wells will have lateral lengths between 10,000 and 16,000-ft. Additionally, super lateral wells make up 7% of the total well population. See Figure 1.

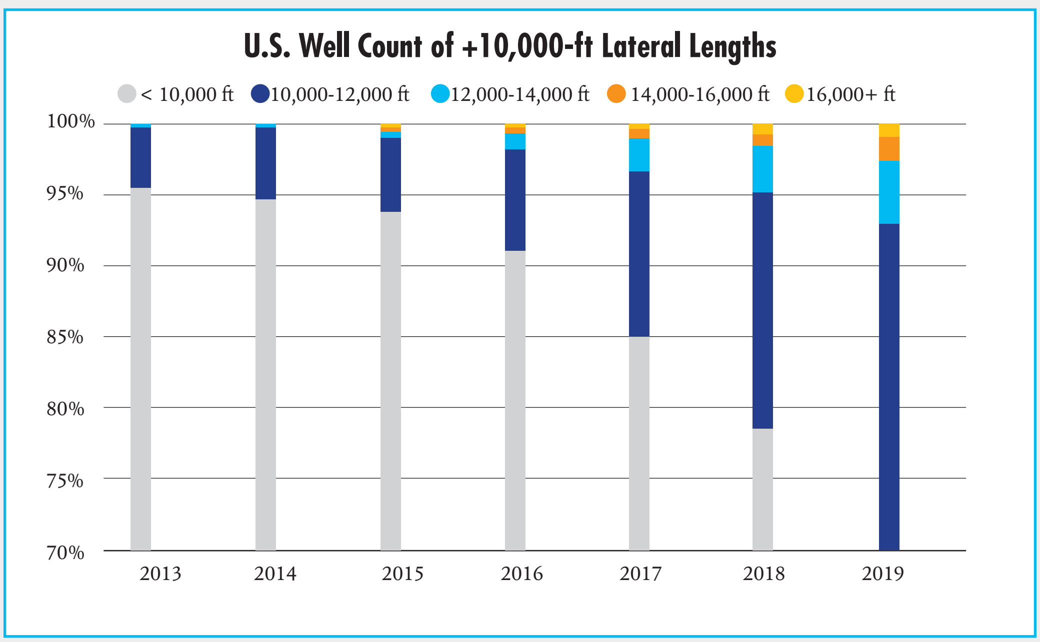

Figure 1: U.S. wells with lateral lengths more than 10,000-ft (Source: drillinginfo)

Figure 2 depicts the number of U.S. wells with laterals longer than 14,000-ft since 2013, showing a consistent growth of about 100% every two years.

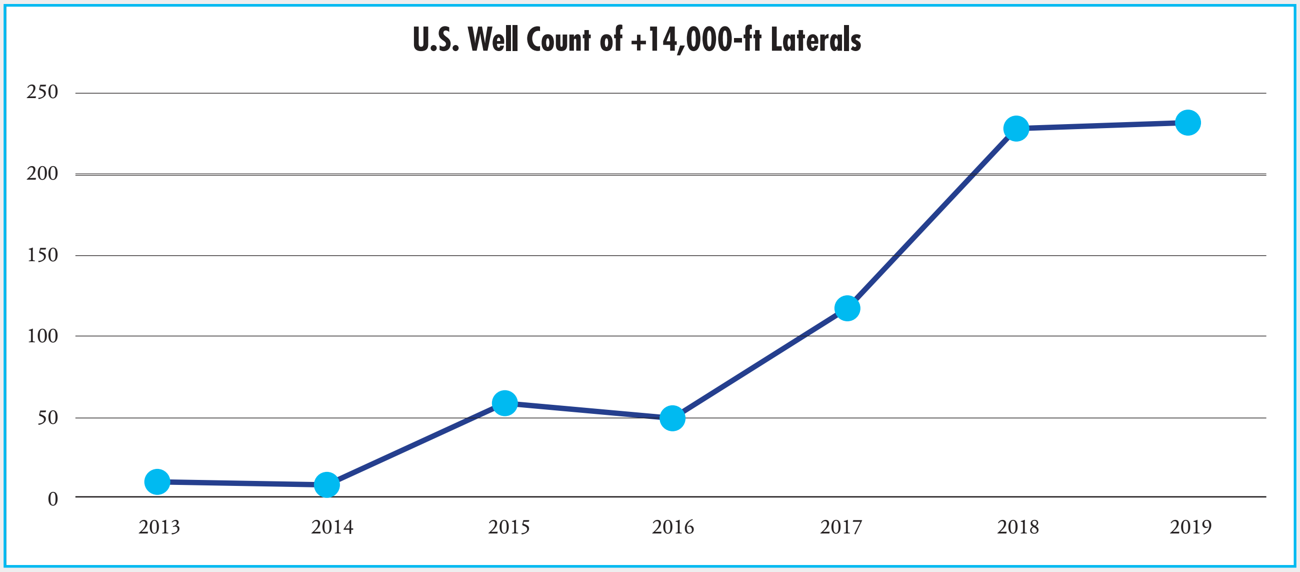

Figure 2: The number of U.S. wells with laterals longer than 14,000-ft (Source: drillinginfo)

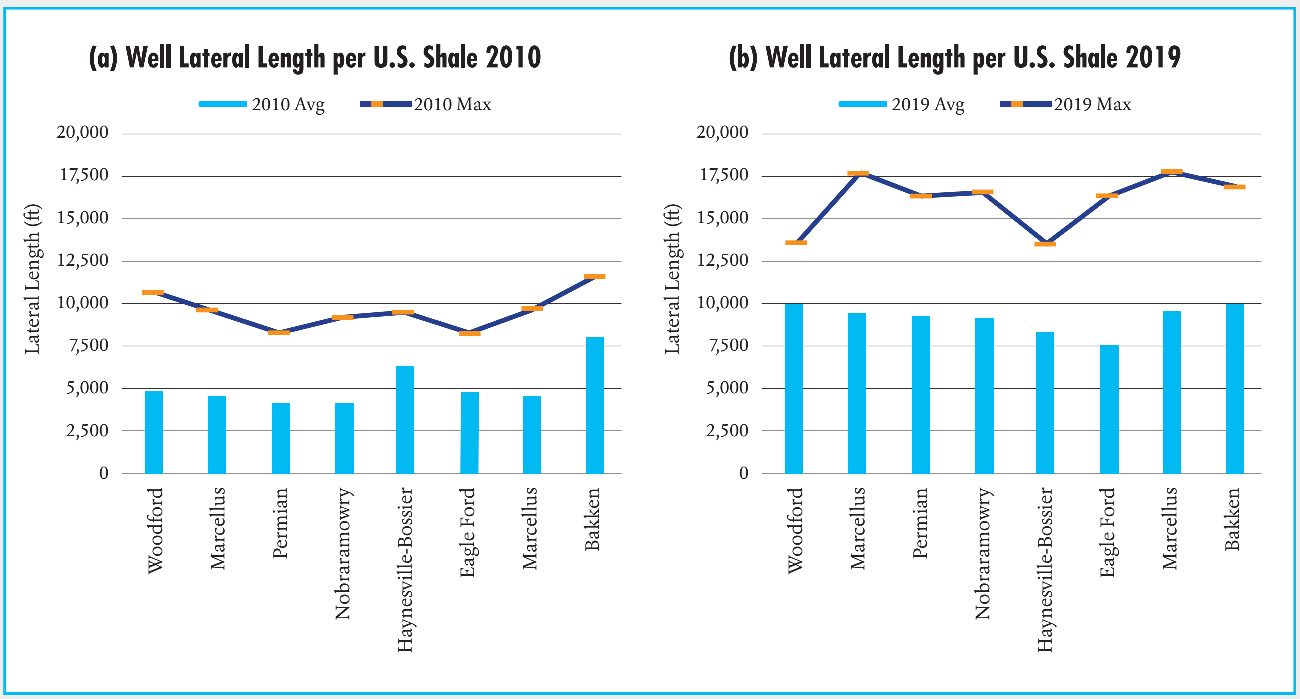

Figure 3: Comparison of the maximum lateral length per U.S. shale between 2010 and 2019 (Source: drillinginfo)

BENEFITS OF DOING BUSINESS WITH ADVANCED COILED TUBING

Compared to full-scale workover rigs, CT has become a crucial part of cutting costs and time. Its use has gradually advanced due to collaboration between operators, service providers, and manufacturers, increasing dependability, and predictability.

The drilling trajectories and new well designs have necessitated the need for extended capabilities. Therefore, well operators and service firms have adopted more sophisticated CT technology to pursue tailored, purpose-fit CT string designs. The logistics of mobilizing these enormous CT rigs to remote locations, along with the rising demand for even larger CT units, have turned into a challenging and intricate problem. These modern CT units are capable of transporting over 28,000-ft of 2.625-in CT weighing as much as 150,000-lbs. To run these larger diameter, extended reach strings, CT injectors have advanced to be able to pull over 160,000-lbf.

In parallel with equipment makers' efforts, manufacturers are moving away from standard CT strings with smaller diameter and toward cutting-edge, custom-engineered strings. These strings concentrated on extending the life and enhancing the reach capabilities, which offer a safe, secure, and low-risk alternative for both well operators and CT service providers. Higher grade CT with yield strengths between 110,000 and 140,000-psi is now available thanks to recent technological advancements in the CT manufacturing sector. These CTs are produced using a quench and tempered process that results in a more uniform microstructure by austenitizing first, then tempering to achieve the desired mechanical properties. Compared to standard CT manufacturing, this method strengthens the steel while also making it more flexible, improving fatigue performance and enhancing resistance to abrasion and corrosion.

The well intervention job design, which is covered in more detail in the following chapter, has evolved to include CT string design optimization as a critical component. This string design optimization also takes regional transit logistics and the capabilities of the surface equipment into account. Another factor that can be decreased is friction, which can be done so by utilizing extended reach tools (ERT) and chemical additives such as metal-to-metal lubricants and fluid friction reducers.

The ERT reduces the effective wellbore friction coefficient while creating an oscillating lateral end load (Sola, 2000). ERTs have been improved by allowing for increased flow rates, optimizing frequencies, and improving effective axial loads that enable CT to penetrate deeper into the well laterals. Metal-to-metal lubricants reduce the apparent friction between the CT and the well casing, enabling even further extended reach capabilities. Fluid friction reducers minimize the fluid drag forces internally to the CT, decreasing pump pressure which in turn will allow for higher pump rates.

The combination of employing specific string designs with ERTs and/or chemical additives to improve lateral accessibility is significant. Depending on how complicated the trajectory of the well is, it may be possible to avoid expensive logistics and specialist surface equipment by using smaller CT diameters and lighter string makeups to reach total depths.

ENGINEERED SOLUTIONS

CT STRING DESIGN

The process of CT string engineering has become increasingly intricate, requiring a thorough understanding of the well conditions, CT operating boundaries (pressures and axial loads), low cycle fatigue, forces, stresses, and anticipated fluid dynamics during the operation. The present mobility weight restrictions of the CT surface equipment are one of the key issues with this new generation of large diameter CT strings that surpass 27,000-ft in length and weigh more than 140,000-lbs. This weight restriction limits the maximum wall thickness that may be used in the CT design, which impacts the string's rigidity and affects the horizontal reach capability. The maximum length of the produced string may be negatively impacted by the weight restrictions. Subsequently, CT service providers are compelled to minimize CT size and depend on the effectiveness of ERTs and fluid additives to achieve desired depths. The main difficulty in extended reach CT string designs is weight limitation, as seen in Figure 4.

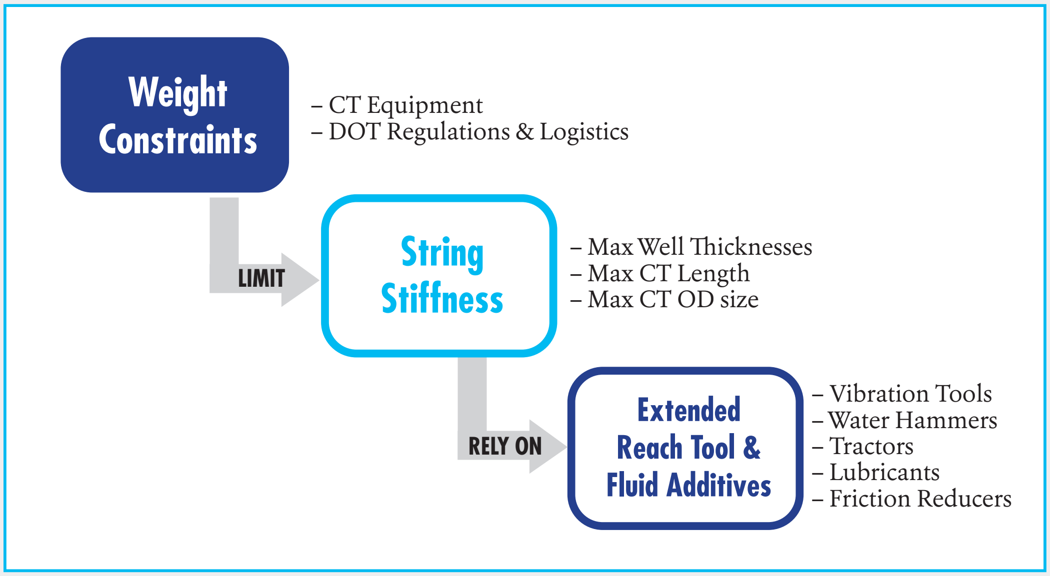

Figure 4: The biggest issue with extended reach CT string systems is weight restriction.

The most widely used CT equipment in the U.S., 2.375-in CTUs, has been utilized to its fullest capacity thanks to technological developments in the CT industry (tubing, tools, and chemicals), enabling service providers to meet the new well criteria. While adhering to the design limitations of the CT equipment, the tubing string composition is engineered for the current well circumstances.

Reducing the CT weight in the horizontal part of the well is the first step in the string design process. By increasing the diameter-to-wall thickness ratios (D/t) in the downhole end, the CT weight can be decreased. To compensate for the pressure and axial load capacity decrease and maintain mechanical qualities, the material yield strength is raised. In order to increase bending stiffness and prevent the onset of helical buckling in the well, the design is then carried out by strategically choosing and placing thicker wall gauges throughout the string (Galvan et al., 2017).

In an hourglass string design, the up-hole end of the CT string, which is frequently not under significant stress, has a thinner wall. The wall thickness selected still offers sufficient axial load capacity to maintain safe overpull values while operations are underway. If properly applied, this string design configuration has no effect on the CT's reach capacity. The key advantages are weight reduction, lower frictional pressure losses in CT because of the larger inner diameters, and lower CT string costs. The grade should be chosen based on CT operating parameter restrictions, such as cycle fatigue restraints, maximum operating pressures, and axial forces.

RAPID WALL THICKNESS TAPERS

The quantity of wall thicknesses and the transition lengths have a big impact on how well the string performs. The arrangement of the transition points is crucial for the string's performance in extended reach CT designs. This covers the changes in wall thickness from thick to thin, the length of each segment that must be present, and bias weld deratings.

In general, the goal of adopting a tapered wall thickness string design is to improve a number of CT string properties, including increasing axial load capacities with a decreased overall string weight. These designs make it easier for CT to operate at higher pressures and deeper depths, which are essential elements in its successful application in unconventional extended reach horizontal wells.

The sections of conventional continuously tapered CT designs exhibit a linear variation in wall thickness along a strip's length (on average 1,800-ft). The primary benefit of a continuously tapered strip section is that all the bias welds are created at the same wall thickness, increasing reliability. However, these strips have physical limitations, such as limited length options and lengthy transitions. As a result, the CT string structure has less design freedom and is generally heavier.

The most recent strip technology offers quick changes between up to four nominal wall thicknesses in a single strip that is 500 to 1,000-ft long. Due to the inherent flexibility of this technique, the tube-weight distribution in the lateral may be more precisely controlled. This is especially important for extended reach CT designs since the arrangement of the wall thickness variations affects, among other things, the stiffness and the force transmitted from the well's surface to its bottom.

The two most popular choices are 0.204-in to 0.156-in and 0.250-in to 0.204-in. Due to this strip technology's adaptability and operating advantages, it was used in many applications and areas, but it was notably effective in unconventional resource projects where CT was subjected to extremely long well lateral lengths.

METHODOLOGY & FINDINGS

2.375-in CT Engineered Solution for ultra-lateral well plug millout and cleanout operations

Analysis of well completions diagrams, surveys, operational procedures, and CT surface equipment available in the Gulf Coast and Permian basins led to the development of 2.375-in CT strings that maximize reach capability in laterals up to 14,500-ft while adhering to strict weight and cost restrictions, thereby enhancing the CT longevity and dependability. Table 1 contains an overview of the various well profiles examined.

Table 1-Well characteristics of analyzed post-job data (Averaged values from same well pad)

Shale Play	Haynesville	Permian	
Measured Depth (ft)	23,800	23,000	23,800
True Vertical Depth (ft)	10,500	9,900	8,700
Lateral Length (ft)	13,000	12,700	14,500
Max Inclination	95°	96°	95°
Max Dogleg Severity */100ft	12.65	17.475	15.667

HAYNESVILLE

The Haynesville formation is an unconventional shale gas resource with depths between 10,300 to 14,000-ft true vertical depth and features an abundance of natural gas. It is located between East Texas and Northwestern Louisiana. Due to the area's high reservoir pressure, operators have invested heavily in development.

The wells that were examined displayed extremely difficult circumstances, including laterals up to 13,000-ft long, a total measured depth (TMD) of 23,800-ft, an inclination of over 95 degrees, and a maximum dogleg severity of over 12 degrees per 100-ft. The wells are completed using tapered casing designs going from 5.5 in 23.0 lb/ft to 5.0 in 18.0 lb/ft. During the initial completions phase in 2019, these wells exhibited some of the longest laterals in the region.
The potential accessibility to TMD and the CT string design's flexibility were limited by the high wellhead pressure exceeding 5,000 psi, commonly observed in the Haynesville shale. This high pressure directly results in high circulating pressure during operations, necessitating a robust string configuration with a thicker wall and higher yield strength for the CT material to withstand the combined pressure loadings, bend cycle fatigue, and deformation during operations (Galvan et al, 2017). The wall configuration of the 2.375-in. CT design ranged from 0.175-in. to 0.236-in., with 130-ksi yield strength.

The 2.375-in string reached TMD in the wells, according to field information acquired during plug-millout operations. The investigation took into account the use of chemical additives as well as the newest iterations of an ERT. Tubing force matching revealed dynamic friction coefficients ranging from 0.25 to 0.24 in the lateral during run-in-hole and 0.19 during pull-out-hole. Post job friction matching also estimated the ERT having a 4,200-lbf oscillating hydraulic end load. To ensure that the desired depth was obtained, a large volume of metal-on-metal lubricants and fluid friction reducers were used. Fluid friction matching was carried out as part of the post-job study and revealed that the employment of fluid friction reducers during the operations significantly reduced pressure losses by more than 50%.

The average apparent friction factors determined by the force matching study on the wells are listed in Table 2 below.

Table 2: Haynesville Wells - Post Frac Plug Millout Operations: CT Apparent Friction Matching

Lubricants	Vibration Tool	Oscillating Hydraulic Load at the End	Well Section	MATCHED Friction Factors	
		lbf		RIH	POOH
✓	✓	4,200 lbf @ 3.75 BPM	Vertical	0.21	0.19
			Curvature	0.25	0.20
			Lateral	0.24	0.21

PERMIAN

It has been projected that the oil reserves in the Permian Basin, which spans western Texas and New Mexico, are larger than the conventional reserves in Saudi Arabia's Ghawar field (Matthews, 2018). It is regarded as one of the greatest oil and gas producing areas in the United States and is made up of the Midland and Delaware basins.

To boost output, this shale has extended well laterals out over 16,000-ft, with a TMD over 26,500-ft. The typical well completion consists of single string, 5.5-in 23.0-lb/ft. The use of CT has undergone extensive testing, and special equipment for 2.625-in CT has been created to support the new weight and length specifications. Nevertheless, 2.375-in CT still provides a cost-effective option for these completions.

To extrapolate the CT performance in numerous wells drilled in West Texas with 14,000 to 15,000-ft laterals, friction matching of post-job data evaluations from other extended reach wells of up to 13,000-ft in the area was used. A thorough CT design and work evaluation showed that using 2.375-in CT diameters makes CT interventions in over 14,500-ft laterals possible. A plug millout job using a 2.375-in designed string made to service these difficult wells is shown in Figure 5.

The chart shows the relationship between the measured surface weights and the values projected by the simulator. According to the software model, the CT string would reach lockup depth at around 3,000 feet from the TMD. However, the actual operation was successful with CT reaching the entire lateral length by increasing the dosage of metal-on-metal lubricants while increasing flow rates. After-job friction matching analysis revealed a 0.23 friction factor which appears to be in line with the pattern of weight readings during the operation.

Table 3 is provided as a guide. According to the post-job friction matching, the ERT delivered about 4,500 lbf. of hydraulic end load. According to the job report, metal-on-metal lubricants were also aggressively injected into the lateral.

Table 3: CT Apparent Friction Matching Post-Frac Millout Permian Super Lateral Well

Lubricants	Vibration Tool	Oscillating Hydraulic Load at the End	Well Section	MATCHED Friction Factors	
		lbf		RIH	POOH
✓	✓	4,500 lbf @ 3.75 BPM	Vertical	0.20	0.19
			Curvature	0.24	0.21
			Lateral	0.23	0.21

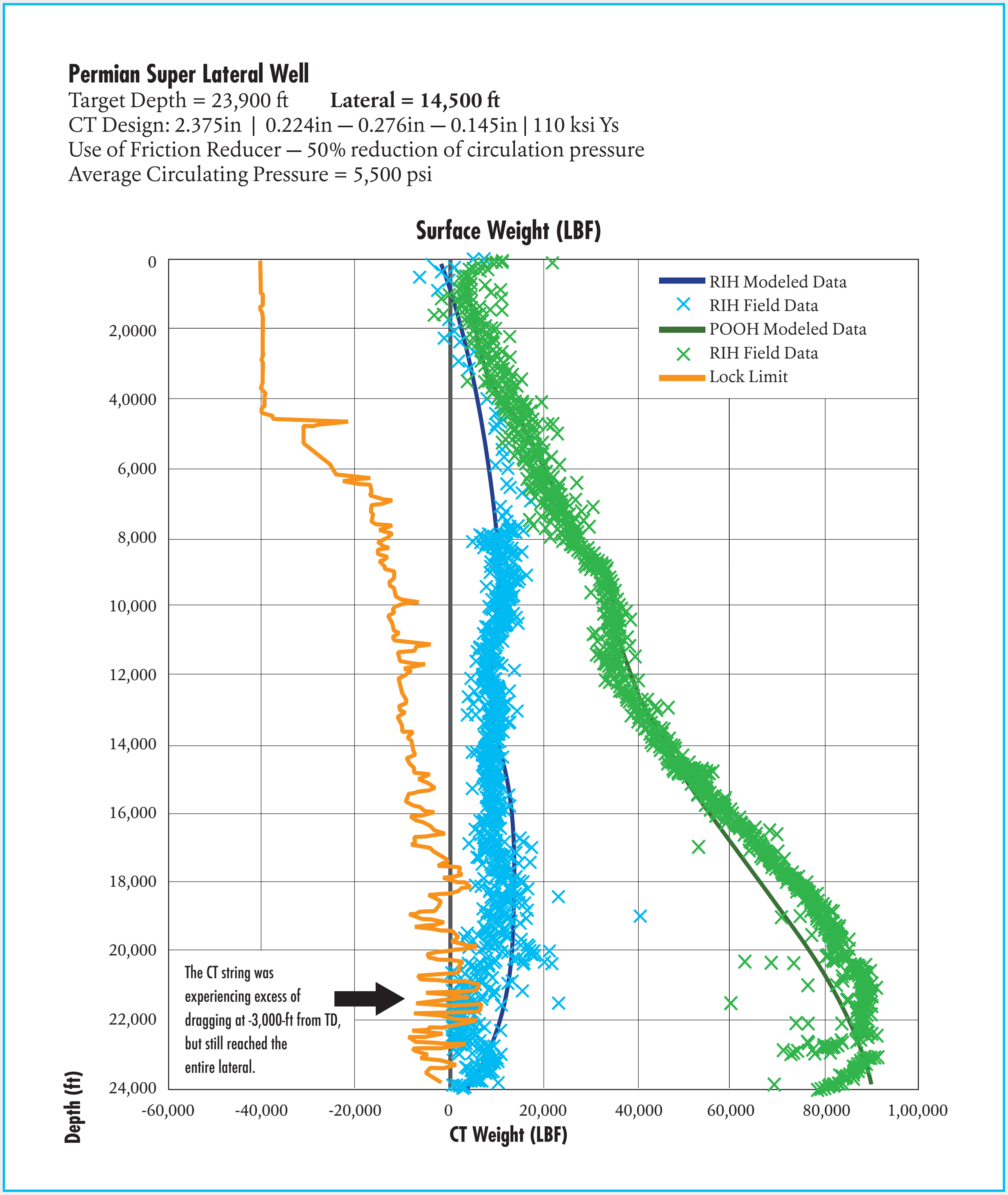

Figure 5: Permian Super Lateral Well 14,500-ft – 2.375-in CT plug millout out operations – Post job friction matching incorporating usage of an ERT and metal-on-metal lubricants.

CONCLUSIONS

Although the industry must make significant technical adjustments for super lateral wells, thorough pre-job analysis, advancements in working fluids, application of highly engineered CT strings with quench and tempered materials, and the most recent ERT designs have enabled successful interventions and increased the operating window of CT on these difficult wells. Super laterals have been criticized for requiring stick-pipe rig modifications. However, case studies have shown that 2.375-in CT produces findings that are noticeably better than expected. By avoiding the expenses and related logistical challenges of switching to larger CT sizes, service firms and operators can make the most of the market's existing equipment and technological foundation, thereby increasing return on investment.

However, recent market data shows that there is still room for lateral length expansion, therefore exploiting the full potential of the 2.625-in CT is the next anticipated step. A thorough examination of forces in several super lateral wells showed that 2.625-in CT is capable of reaching TD in laterals longer than 16,500-ft. 2.625-in CT strings over 28,000-ft are already being produced. These strings reach a weight of more than 150,000-lbs. setting a new record for CT interventions in the United States.

> To bridge the gap between drilling innovations and well intervention, robust CT technology with excellent durability and dependability is still required. Therefore, to undertake low-risk super lateral completions on a bigger scale, technological advances in surface equipment, downhole tools, chemical additives, and CT string design, as well as improved field operational techniques and logistics, are essential.

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