CARBON FIBER SUCKER RODS INCREASE PRODUCTION, REDUCE WEAR

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ABSTRACT

Carbon fiber sucker rods were first installed in wells in 2015, and significant material and design improvements have been made since. Originally developed to rod pump the deepest wells with small-diameter tubing, high-strength, light-weight carbon fiber rods are optimal for rod pumping through the build section in pad-drilled wells. This paper will show how carbon fiber rods reduce friction and side-wall loads through wellbore deviations, and enable higher ESP-like rates of production when operated with long stroke beam pumping units.

INTRODUCTION

Pad-drilled wells have been steadily increasing in popularity since 2006, and as of 2014, represented about 75% of all new wells drilled in the Bakken and Eagle Ford, and about 21% of new wells drilled in the Permian[1]. Pad-drilled wells present operational challenges for sucker rod pumping (SRP) due to the wellbore deviation from vertical, causing sucker rods to have increased contact against tubing. Increased rod/tubing contact results in greater lifted load due to mechanical drag friction load, and greater side-wall loads (SWL) between rod and tubing.

Greater drag friction load increases lifting cost, causes wear & tear on surface pumping units, increases sucker rod fatigue, and reduces the overall fluid lifting capacity of the SRP system. Higher SWL results in faster wear rates of rods and tubing, and shorter mean time before rod/tubing failures.

The magnitude of drag friction load depends upon 1) coefficient of friction between rod & tubing, 2) well tortuosity (i.e., number and degree of wellbore deviations), and 3) the magnitude of the lifted load. SWL is dependent almost entirely upon well tortuosity and lifted load, with the coefficient of friction having minimal effect on SWL (exclusive of its contribution to lifted load). Shallow well deviations produce greater drag friction and SWL than the same deviation angle deeper in the well. This is due to the heavier lifted load passing through the shallow deviation. The “build” section of a well (Figure 1) is often the location of the highest SWL and drag friction because it is shallow (where lifted load is greatest), and normally the well’s first point of deviation from vertical.

WELL TORTUOSITY AND FRICTION/SWL

“Dog-leg severity per 100 ft.” (DLS) reflects the change in wellbore inclination and azimuth between two consecutive survey depths. The distance between consecutive survey depths may vary, so for meaningful comparison, the DLS is projected as being over a distance of 100 ft., regardless of whether the distance between survey depths is greater or less. The DLS is an indicator of the severity of wellbore tortuosity expressed in degrees of deviation.

Side-wall load (SWL) is the normal force of rods against tubing expressed as lbs. of force per 25ft. rod (the SWL term assumes all rods are 25 ft. long). Friction is related to normal force according to Amonton’s second law of friction which says the magnitude of friction force (F_f) is proportional to the magnitude of normal force (F_N). The ratio of friction force to normal force is the coefficient of friction (μ).

$$\mu = \frac{F_f}{F_N}$$

The dimensionless coefficient of friction (μ) for steel rods against steel tubing is generally accepted to be .2. In other words, the normal force of rods against tubing in a wellbore deviation is 5 times the drag friction force resisting the upward lift of rods through the same deviated section.

The Capstan equation, commonly used to calculate the friction and normal force of a cable passing around a stationary spool, is useful for calculating normal force (F_N) and friction force (F_f) of rods against tubing through a wellbore deviation.

Capstan Equation: $\text{Load 1} * e^{(\theta * \mu)} = \text{Load 2}$

In a wellbore deviation survey, the inclination and azimuth at each measured depth define a vector in 3-dimensional space. Two consecutive vectors define a circle of deviation. Theta (θ) is the angle (in radians) formed between the two radii that are perpendicular to the two vectors of the circle of deviation. Theta can be calculated from the DLS as shown in Figure 2. The Capstan equation is a reasonable method of calculating the drag friction and SWL load for sucker rods passing through a deviated section of the well bore because the ratio of the sucker rod radius to the radius of the circle of deviation is significantly small. If that were not the case, additional forces would be acting on the rods to cause them to bend through the deviation. Figure 3 shows a simple calculation for drag friction and SWL for a 20,000 lb. steel rod load through a 5° DLS. The friction increase due to the 5° DLS at 1,500 ft. is 175 lbs., and the SWL is 437 lbs.

Table 1 uses the data in the Figure 3 example to show the relationship between coefficient of friction, lifted load, and deviation angle (or DLS), to friction load and normal load (or SWL). The data shows that whatever the percentage change in rod load, coefficient of friction, or deviation angle, will be the same percentage change in drag friction load. However, any change in the coefficient of friction has negligible effect on the SWL. The only way to reduce SWL is to reduce the DLS or to reduce the lifted load. Since a well is already drilled and its DLS is fixed, <u>the only option to reduce SWL is to reduce the lifted load</u>.

Lifted Load & Components of PPRL

The maximum lifted load in each pumping cycle is the peak polished rod load (PPRL). In a pumping cycle, the PPRL is made up of the following loads: 1) fluid load, 2) buoyant rod weight, 3) drag friction load, and 4) dynamic loads. In an example 9550’ pad-drilled Bakken well producing 300 bpd with an 86 steel rod string (+ 700’ of 1” sinker rod), pumping 8 spm with a 1-3/4” pump and 168” stroke length, the PPRL of 37,282 lbs. breaks down into the following as a percent of PPRL: fluid load 24%, buoyant rod load 51%, friction load 8%, dynamic load 17%. (See graph in Figure 4). This graph shows that drag friction load is relatively independent of the pumping speed, whereas dynamic loads are very much dependent upon the pumping speed.

If the coefficient of friction were cut in HALF (by using poly-lined tubing or low friction couplings), the drag friction load would also be cut in half, but the PPRL would only be reduced by only 4%. Dynamic load is a function of rod mass, rod acceleration (spm), and the rod modulus of elasticity, and is calculated using the wave equation. Dynamic rod load could be reduced almost in half by slowing the pumping speed down from 8 spm to 4 spm, but the PPRL would be reduced by only 8%. Slowing down the unit would come at a cost of the daily oil production being cut to less than half. To make up for the lost production, the pump diameter could be increased to 2”. In this case, the fluid load would increase to 32% of the PPRL. However, even with the larger pump diameter, production would be still less than half of 300 bpd because all the greater fluid load does is cause the rods to stretch more, greatly reducing the downhole pump stroke. Finally, to overcome excessive rod stretch, stiffer 1-1/8” steel rods could be run all the way to the pump, but even with the stiffer rod string, the production rate would still be less than 200 bpd. In this case, the heavier rods would cause the PPRL to now be over 53,000 lbs. which is 43% heavier than the original PPRL and is opposite the objective of reducing the lifted load.

Light-Weight Carbon Fiber Rods

The best solution to reduce PPRL is to reduce the buoyant rod weight. Considering that buoyant rod weight represents 51% of the PPRL in the previous example, any reduction in this component load has the greatest percentage impact on reducing the PPRL.

Sucker rods made of light-weight, high-strength carbon fiber are an effective solution to greatly reduce the buoyant rod load, and thus the PPRL. The buoyant weight of 5/8” diameter carbon fiber (CF) rods is 7.5% of the buoyant weight of 1” steel rods (ST), and 23.5% of the buoyant weight of 1-1/4” fiberglass (FG) rods. See table 2. Each of these rod types is utilized in the top section of the rod string where the lifted loads are greatest. Like FG rods, CF rods must be in tension on both the pumping unit up stroke and down stroke. CF rods have a modulus of elasticity of 22 million psi. compared to ST at 30 million psi. and FG at 7 million psi. The lower the modulus, the greater the rod stretch.

CF rods have a tensile strength of 275,000 psi which is nearly double the 140,000 psi. tensile strength of UHS ST rods, and more than double the 115,000 psi. strength of FG rods. Not only do CF rods have greater tensile strength, they are able to use a greater percentage of their tensile strength while operating under cyclic loading. In SPE 28523 Lea et. al state*, “At 10 million cycles, carbon fiber composites operate at 60% of their ultimate strength, while steel operates at 40% and fiberglass operates at only 20% of its ultimate strength and is still decreasing with additional cycles.”*[2] The graph in Figure 5 shows this comparison[3]. The Modified Goodman Diagram for each sucker rod type is included in all SRP design and evaluation software programs and is utilized in calculating the percentage of rod strength under cyclic loading conditions.

The Build Section

A well in Upton County, TX kicks off from vertical at 712 ft. and builds to a 6.6° inclination over 369 ft. The DLS at two survey locations through the build section is greater than 2°. A roughly 7° inclination angle is held through the tangent section of the well before dropping to vertical from 5,500 to 6,000 ft. (Figure 6). The operator wants to produce 500 bpd from 8,625 ft. in 2-7/8” tubing. One option is to use continuous rods with a 96 taper and a Long-stroke linear unit with 366” stroke length and a 2-1/4” tubing pump running at 3.2 spm. The PPRL of this system is predicted be 46,727 lbs. The maximum SWL through the build section is predicted to be 424 lbs. Another option is to run 4,050 ft. of CF rods with 7/8” ST and sinker bars below, with a C1280-365-240 pumping unit, 1-¾” insert pump, pumping 7.3 spm. The PPRL is predicted to be 27,840 lbs. The maximum SWL through the build section is predicted to be 267 lbs. (Figure 7). (Note: FG rod designs exceeded the gearbox torque rating of the C1280-365-240 unit, so were not an option).

With CF rods, the average rod load through the build section at 26,011 lbs. is 38% lower than the average all-steel rod load through the build section at 41,515 lbs. Therefore, as discussed previously, both SWL and drag friction load through the build section will also be reduced by 38% with the CF rod design. It is reasonable to expect that a 38% reduction in SWL with CF rods will result in reduced rod/tubing wear and longer rod/tubing run life. Some operators run poly-lined tubing through the build section when the SWL exceeds 300 lbs. to protect both rods and tubing from excessive wear. The lower SWL’s resulting from the CF rods through the build section reduces the need for this additional protection and expense.

Tubing scans show that CF rods with small 1-5/8” diameter end-fittings are much less destructive than 1” ST rods with 2” diameter slim-hole couplings. A well in the Rockies had 3,150 ft. of CF rods on top of an 86 ST rod taper plus sinker bars. The well was pulled for a tubing leak. The tubing scan showed severely worn red-band tubing across the entirety of the 1” ST rod section. (Figure 8). However, rod wear across the majority of the CF rod section (above the 1” ST) was nearly all yellow-band with some green, blue, and red just above the 1” rods. This particular well was mostly vertical, however its tubing anchor released which likely contributed to the excessive wear of 1” rod couplings against tubing. A plunger-effect can occur between 1” rods with 2” OD couplings and 2.441” ID of 2-7/8” tubing. When tubing is unanchored, excessive tubing movement can occur in this section of tubing, resulting in excessive wear. The CF rods above the 1” ST were guided and operating at greater rod loads than the 1” ST. The CF rods however experienced no plunger effect with the tubing and rod wear was minimal. Both the yellow-band tubing and the CF rods were re-run, while the 1” couplings and red-band tubing were replaced.

CF Rods: High Production Rate

Carbon fiber rods enable higher production rates from beam pumping systems than can be achieved with either ST or FG rods. CF rods, with a buoyant weight of 7.5% of ST rods and 23.5% of FG rods, increase the fluid lifting capacity of the pumping unit because of its not having to lift as heavy a load of sucker rods. The greater fluid production is achieved by the ability to pump with longer pumping unit stroke lengths or with larger pump diameters.

It is unusual to find beam pumping units in the Permian Basin with a maximum stroke length greater than 192 inches. This is because to rod pump a 10,000 ft. well with ST or FG rods at a stroke length greater than 192 inches, the pumping unit would typically require an 1824 or 2560 gear reducer, which are uncommon. However, with CF rods, it is entirely possible to pump 240 inches with only a 1280, or even a 912 gear reducer, without exceeding the gear reducer torque.

CF rods have successfully operated in two wells with 240 inch stroke lengths. A well in California produced 637 bpd from 9,989 ft. with 3,870 ft. of CF rods, 1-3/4" pump, pumping 7.4 spm. The PPRL was 29,500 lbs. The gear reducer was 2560 but the actual torque load on the pumping unit was measured at 50% of GB torque, or 1280. Another well in Pecos County, TX with carbon fiber rods is currently operating with a C1280-365-240 pumping unit running 6.6 spm with a 1-1/2" pump set at 8.950 ft. in 2-3/8" tubing. The well produces around 600 bpd with a PPRL of 17,117 lbs. As of August 2021, the CF rods have been operating in this well for 22 months.

CF Rods: Greater Production Range

In the case of a highly deviated Permian well with a pump depth of 11,300 ft., an operator wants to make the switch to SRP from ESP as early as possible without any reduction in production rate. Their additional desire is to install a rod pumping system that can operate the full range of fluid draw down, ideally from a fluid level of 5000 ft. to 11,000 ft. without a pulling unit intervention to replace the pump. The goal is for any adjustments to displacement to be made with the surface equipment. The variable frequency drive would make the necessary pumping speed adjustments, and changes in the pumping unit stroke length would also be made on the surface pumping unit. As the fluid level drops, the fluid lifted load increases which also increases the torque load and structure load on the pumping unit. Adjusting the pumping unit stroke length to the next shorter stroke reduces the torque load on the pumping unit. However, to maintain production following a stroke length reduction, the spm needs to be increased, which would then increase the dynamic loads.

Considering a large C1824-427-300 pumping unit operating at a maximum speed of 7.5 spm, an 86 UHS ST string can only operate with a maximum pump diameter of 1-1/4" without overloading rods and the pumping unit as the fluid level is drawing down. The ST rod system cannot run above 6 spm without exceeding the gear reducer torque, and the unit would have to be stroked back as the fluid load increases due to the dropping fluid level. FG rods, being lighter than steel, allow for the next larger 1-1/2" pump diameter. Greater production can be achieved with a 60% 1-1/4" FG rod string. However, like the ST rods, the FG system must be slowed down or stroked back when the fluid level reaches 8,000' so as not to over-torque the pumping unit. The highest production over the 5,000 to 11,000 ft. fluid level range can be achieved with a 47% CF rod string and a 1-3/4" pump, without overloading the pumping unit through the entire range of draw down. (Figure 9). At the 10,000' fluid level the pumping unit speed would need to be reduced to 6.5 spm to keep the ST rods below the CF rods from exceeding their stress rating. The predicted PPRL of the CF system with a 1-3/4" pump and 11,000' fluid level is 34,562 lbs. which is less than the predicted PPRL of the ST rod system at the 5,000' fluid level with a 1-1/4" pump at 36,450 lbs.

Finally, if the operator were willing to set aside their goal of using the same pump diameter through the 5,000' – 11,000' draw down range, greater production could be achieved at the shallower fluid levels. The operator could run a 2" pump with the CF rod system and produce 985 bpd at a 5,000' fluid level. When the fluid level dropped to 8,000', the operator would need to replace the 2" pump with a 1-3/4" pump which could then be used through the remainder of the fluid draw down. (Figure 10)

Higher production rates from long-stroke conventional beam pumping units and CF rods allow operators to switch from ESP to SRP before ESP pump intake pressures reach 800 psi., when gas slugs present operational problems for ESP's. For some operators, the higher rates with CF rods and long-stroke units could allow eliminating the ESP step altogether and go directly to SRP from natural flow or gas lift assisted production.

CONCLUSIONS

- The magnitude of drag friction load and side wall load through wellbore deviations is directly proportional to the magnitude of the rod load at the deviation.
- Considering that a well's tortuosity (DLS) is fixed, the only way to reduce SWL is to reduce lifted load.
- The Capstan Equation is an effective method for predicting and comparing rod/tubing drag friction and side wall loads in deviated sections of the wellbore.
- The most effective way to reduce the rod load is to reduce the buoyant weight of rods. Carbon fiber sucker rods have a buoyant weight that is 7.5% the buoyant weight of 1" steel rods and 23.5% the buoyant weight of 1-1/4" fiberglass rods.
- In pad-drilled wells with a shallow build section, carbon fiber rods in the top section of the rod string (instead of 1" steel rods) can lower drag friction loads and side-wall loads through this deviated section by 38%.
- Carbon fiber rods and long stroke conventional units can achieve the highest production rates possible from a sucker rod pumping system.
- Carbon fiber rods with long stroke conventional units are able to maintain highest production rates with the same pump diameter through the full range of fluid draw down, eliminating the need for costly rig interventions to change the pump size.

REFERENCES

[1]Enverus.com blog, *"On the Launch Pad: The Rise of Pad Drilling"*, Kevin Thout, February 4, 2014
[2]SPE 28523 Space Age material Technology Extends Beam Lift Capacity, J.F. Lea et. al 1994
[3]Delmonte, J., "Properties of Carbon/Graphite Composites", 1987, published by Krieger Publishing Co.

Table 1 – Rod load, Coef. of friction, and DLS effect on Friction load and SWL

Fig. 3 Example

DLS = 5° /100'

d = 50' distance between survey depths

$\theta = \frac{(DLS) * (d)}{100} = \frac{(5)*(50)}{100} = 2.5° = 0.0436$ radians

$\mu = 0.2$

$$\text{Load 1} * e^{(\mu * \Theta)} = \text{Load 2}$$

VARY COEFFICIENT OF FRICTION										
	Load 1	θ rad		µ	%	Load 2	friction lbs.	%	SWL	%
BASE CASE	**20,000**	**0.0436**		**0.2**	**100%**	20,175	**175**	**100%**	**438**	**100.0%**
				0.1	50%	20,087	87	50%	437	99.8%
				0.25	125%	20,219	219	125%	439	100.1%
				0.3	150%	20,264	264	150%	439	100.2%
				0.4	200%	20,352	352	201%	440	100.4%

Friction load varies directly with % change to µ. SWL is <u>not affected</u> by any change to µ. SWL is the same regardless of µ

REDUCE LOAD BY 25%										
%	Load 1	θ rad		µ		Load 2	friction lbs.	%	SWL	%
75%	15,000	0.0436		0.2		15,131	131	75%	329	75.0%
				0.1		15,066	66	75%	328	75.0%
				0.25		15,165	165	75%	329	75.0%
				0.3		15,198	198	75%	329	75.0%
				0.4		15,264	264	75%	330	75.0%

Friction load and SWL are directly affected by % change in rod load. Cut rod load 25%, then friction and SWL reduced by 25%

CUT DLS IN HALF										
	Load 1	θ rad	%	µ		Load 2	friction lbs.	%	SWL	%
	20,000	0.0218	50%	0.2		20,087	87	50%	219	49.9%
			50%	0.1		20,044	44	50%	218	49.9%
			50%	0.25		20,109	109	50%	219	49.9%
			50%	0.3		20,131	131	50%	219	49.8%
			50%	0.4		20,175	175	50%	219	49.8%

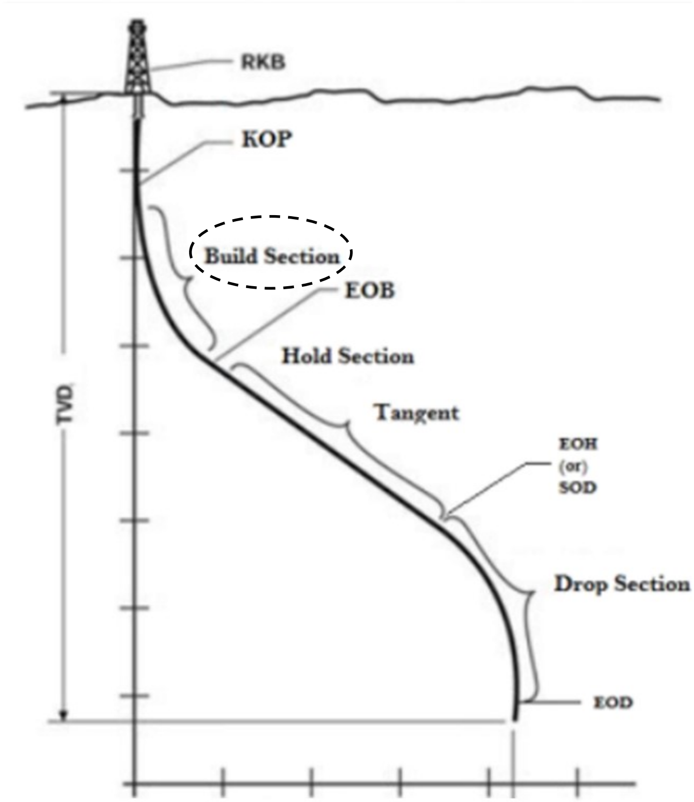
Friction load and SWL are directly affected by % change in DLS. Cut DLS in half, then friction load and SWL reduced by half

Table 2 – Buoyant Sucker Rod Weights

Rod type	Rod Length ft./rod	Dry weight* lbs./rod	Vol displaced* in^3	Wt. displaced^ lbs./rod	Buoyant wt. lbs./ft.	CF buoyant wt. as % of others	Buoyant wt. lbs. per 1000'
1" ST w/ SH coupling	25	72.4	251.7	9.09	2.533	7.5%	2,533
1-1/4" FG w/SH coupling	37.5	50.3	557.7	20.14	0.804	23.5%	804
5/8" CF	37.5	12.6	152.6	5.51	0.189	---	189

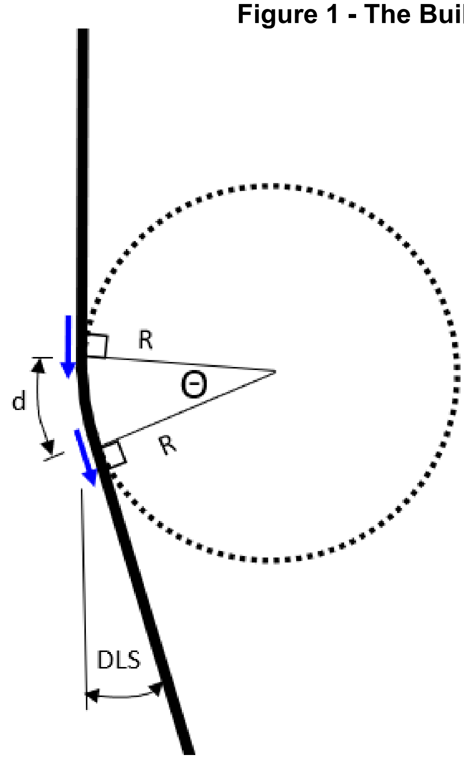
* with coupling

^displaced fluid density, lb./gal 8.34 (fresh water)



Victoria Pons, Gulf SPE Chapter presentation on Wave Equation Jan. 2021

Figure 1 - The Build Section



$$\Theta = \frac{(DLS) * (d)}{100}$$

(convert Θ to radians)

Figure 2 – DLS, Theta Angle, & Circle of Deviation

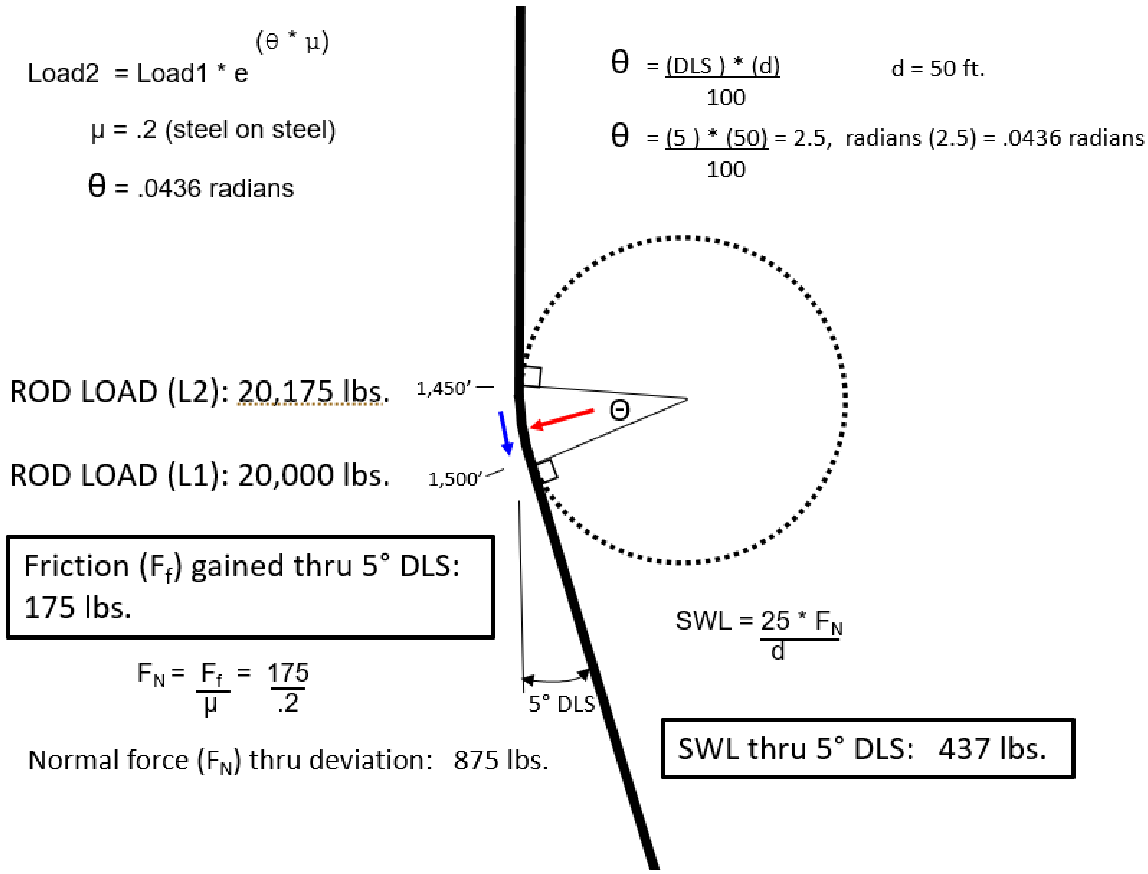


Figure 3 – Capstan Calculation of Drag Friction & SWL

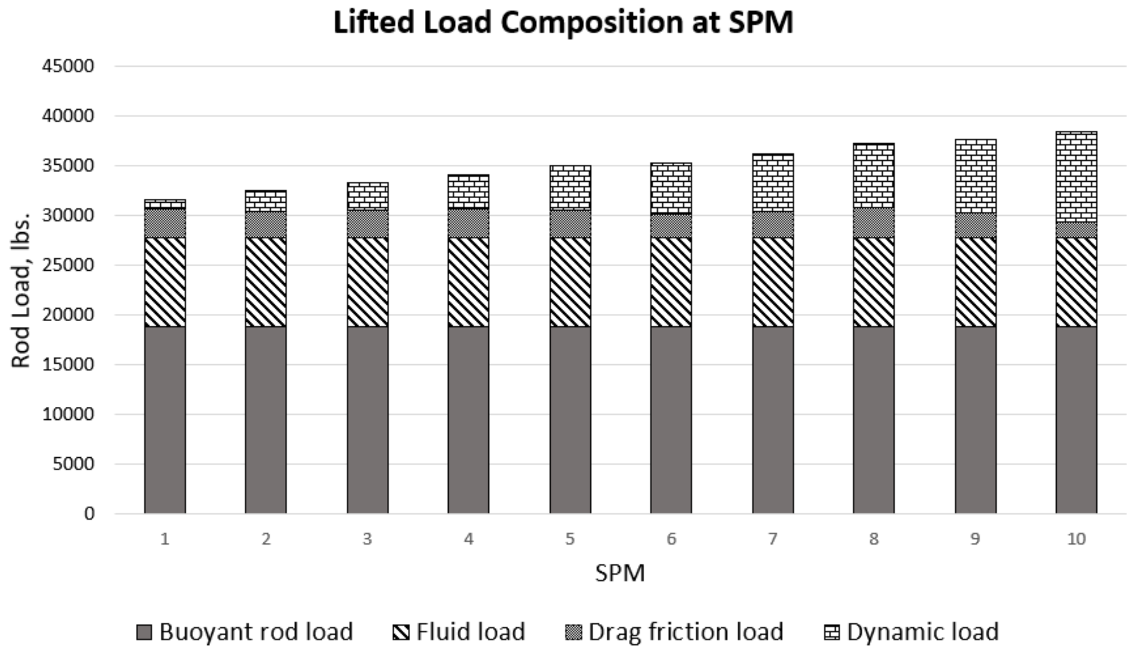
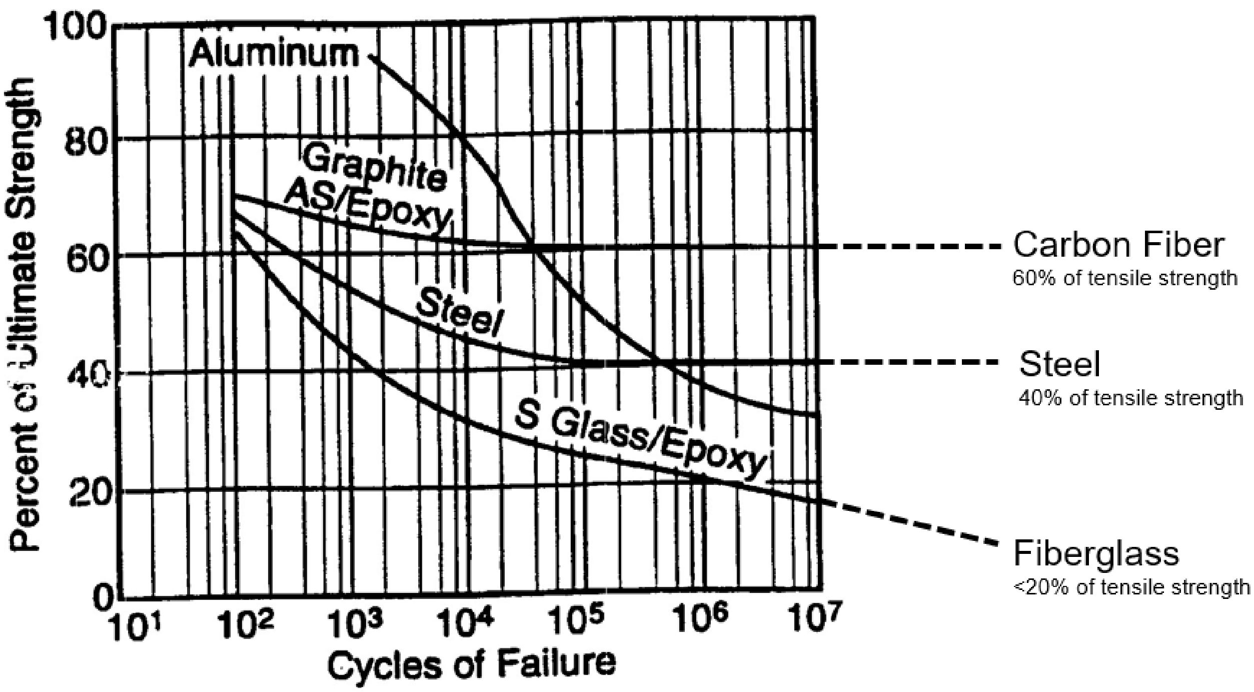


Figure 4 - Load Components of PPRL



Excerpt from SPE 28523, 1994 Delmonte, J., "Properties of Carbon/Graphite Composite%" 1987, published by Kriager Publishing Co.

Figure 5 – Fatigue Resistance of Different Materials

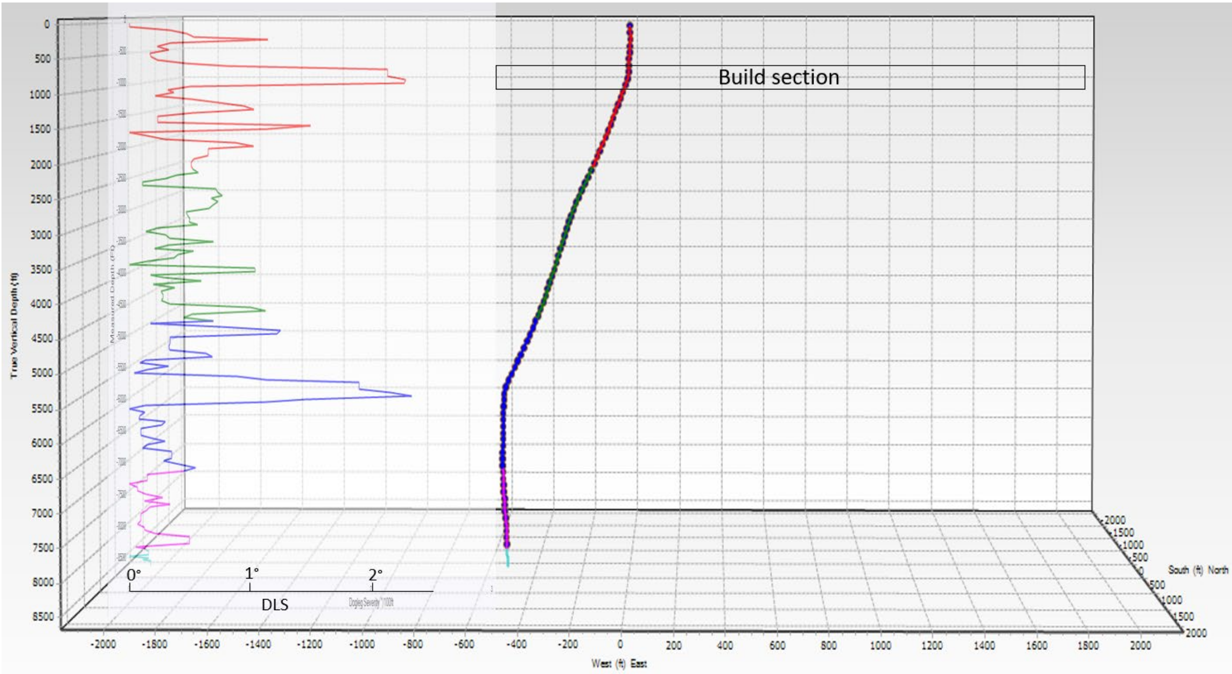


Figure 6 - Well Profile: 2° DLS through Shallow Build Section

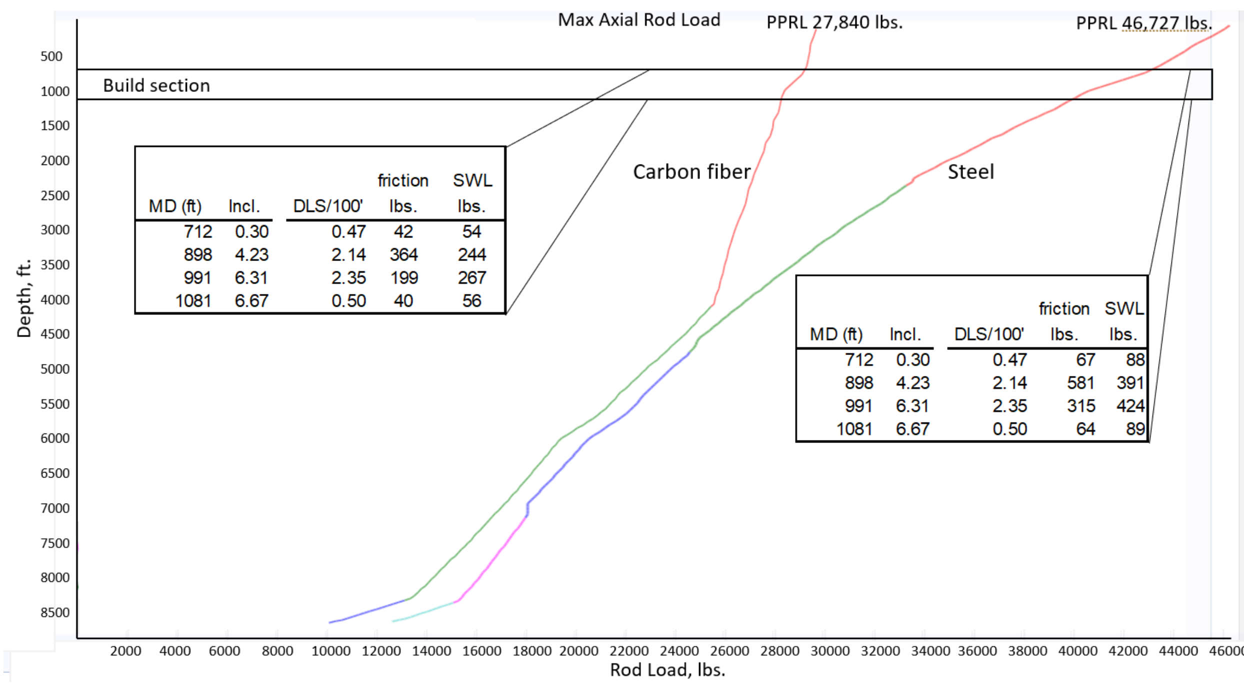


Figure 7 – Max Axial Rod Load CF vs. ST (SWL, and Drag Friction through the Build)

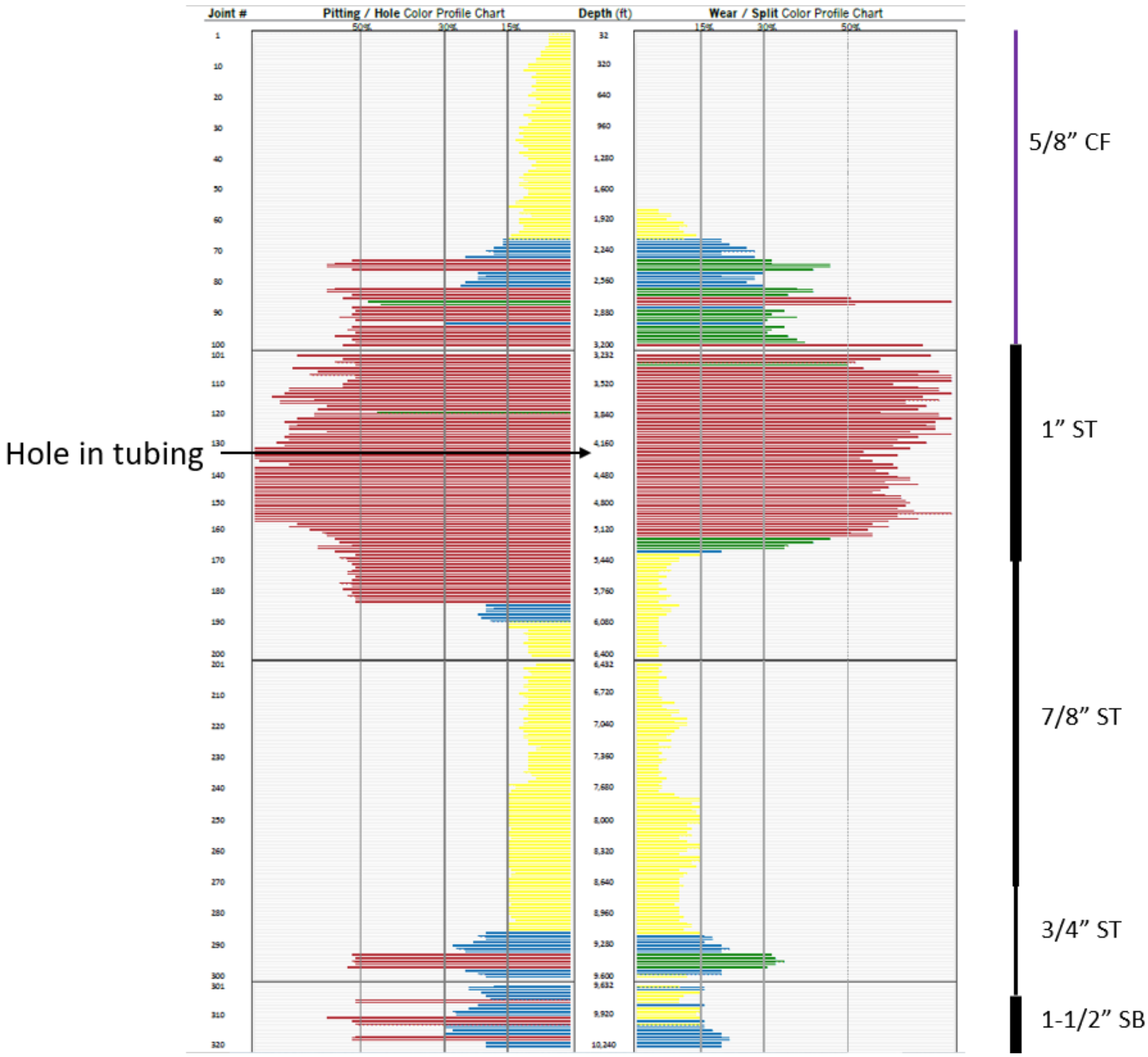


Figure 8 - Tubing Scan: High Wear Across 1” ST Rods

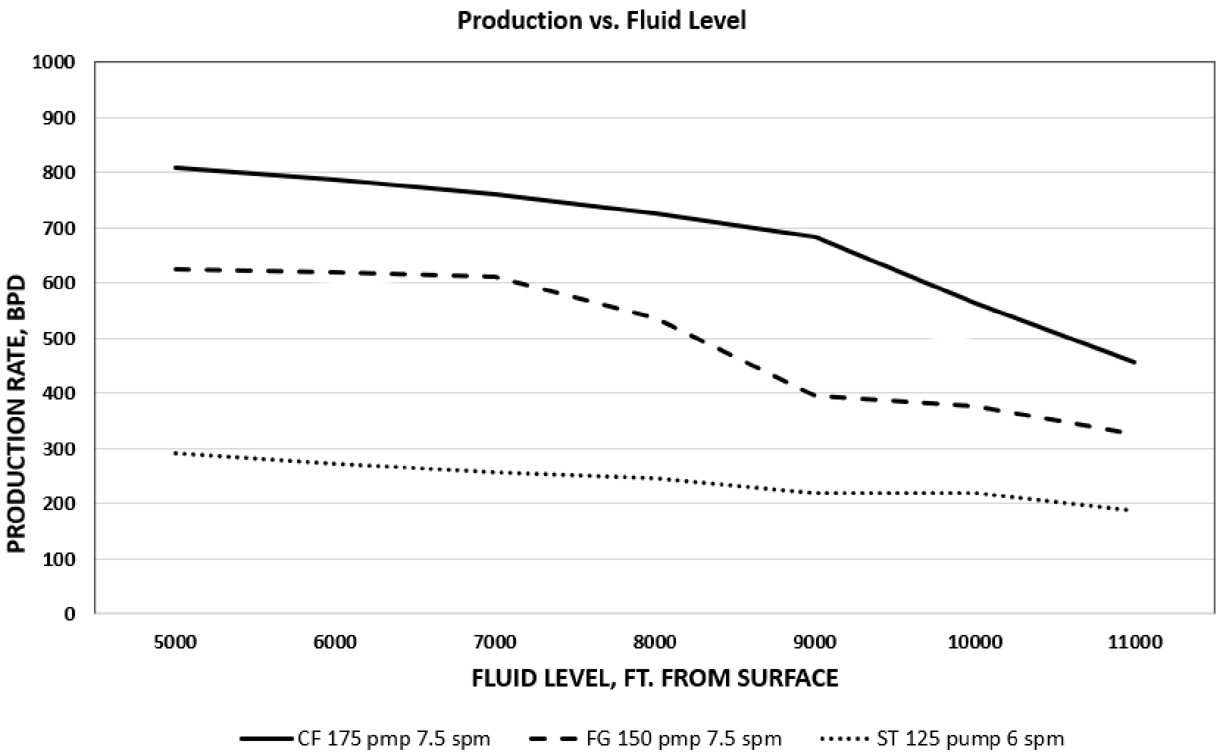


Figure 9 - Production vs. Fluid Level: CF, FG, & ST (PD 11,300')

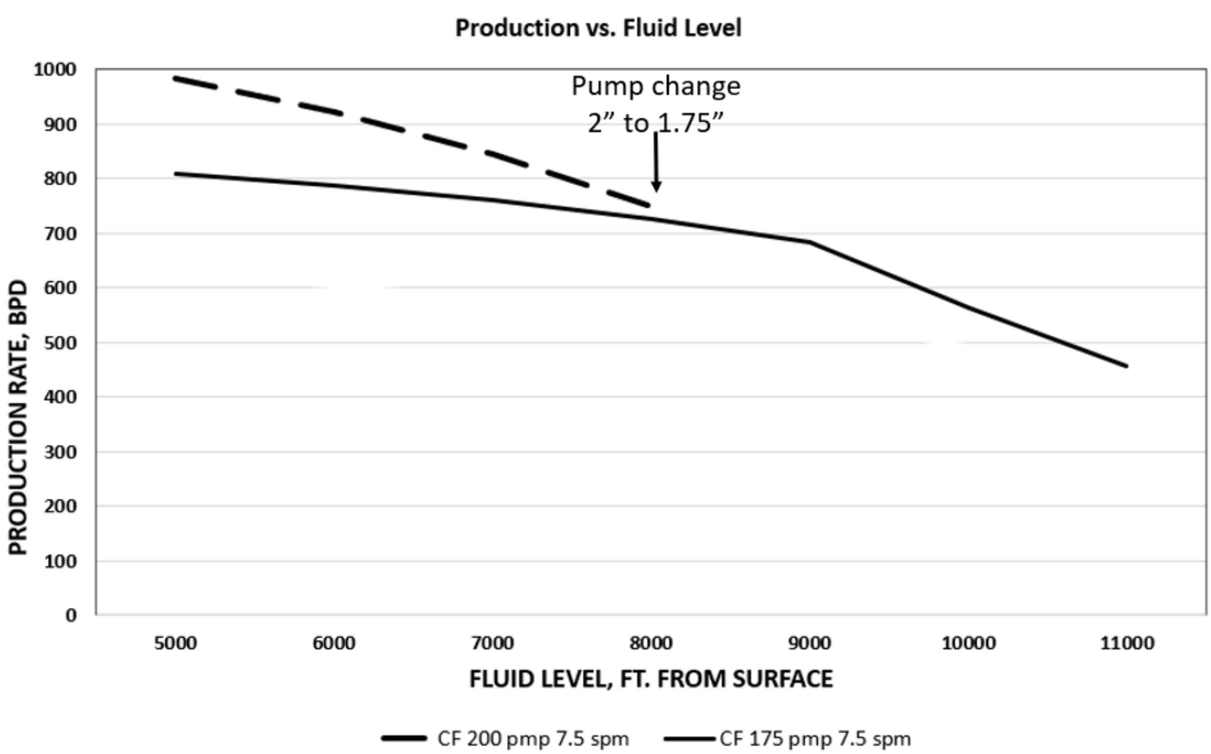


Figure 10 - CF Production vs. Fluid Level with Pump Change (PD 11,300')