DYNAMOMETER CONCERNS

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INTRODUCTION:

This discussion is on what can Predictive and Diagnostic programs show in regard to loading and especially with negative loading in the rods above the pump. Since this location is in an area where much of the rod/tubing wear occurs, this discussion centers on what can be expected from Predictive and Diagnostic wave equations program results.

PREDICTIVE CAPABILITIES:

The predictive wave equation predicts the bottom hole dynamometer card, the surface dynamometer card, the rod string movements, and stresses in the rods. The original program had as the boundary condition at the pump zero Effective load at the bottom of the bottom rod, which means zero compression that causes buckling but still has True compression associated with the buoyancy force. This has been modified by some programs by allowing the user to input some fixed value of pump resistance or friction on the down stroke (typically 200 lbs. as a default), and some programs to calculate the resistance by the drag of the flow through the TV and viscous resistance between the plunger and the barrel. Regardless, the predictive program cannot tell if there is actually compression in the bottom rod in the well, but can simulate it if the user inputs some form of pump resistance as the plunger is pushed into the barrel. Otherwise the bottom card from the predictive programs has no external loads that cause compression and tend to buckling. Table 1 shows values that can buckle rods.

However, there is another factor that adds confusion in some cases, and that is whether or not the bottom card is plotted using a True or Effective Load (see Figure 1). Without a lot of discussion, the Effective Load does not include the buoyancy load and the True Load does. It can be shown that when the Effective Load is zero then there is no tendency to buckle the rods even though there is negative or compressive True Load from buoyancy forces at the bottom of the bottom rod. This is also a concern for the diagnostic results, but this is discussed later in the text. One popular wave equation program only presents bottom cards with some portion of the card well below zero using True forces while another popular wave equation program plots bottom cards mostly using Effective loads with the bottom card sitting on the zero line or a little below if the pump resistance is input.

Before beginning, Figures 2a and 2b show what shape the bottom cards could be with a full bottomhole pump and with incomplete fillage in the pump. Whether or not they show compression is discussed below.

TRUE AND EFFECTIVE LOADS:

Figure 3 shows a predictive bottomhole card plotted with Effective Loads and no programmed pump resistance so the card sits on the zero line. Note that the TV opens about 12 inches before the fluid is reached with a PIP of 555 psi and at about 2 inches with a PIP of 55 psi. A small percentage of the card would sit below the zero line if any pump resistance is used. More on this in the following Diagnostic Section.

For the purpose of this paper, all examples were generated based upon a M160-246-86 unit in the 3rd crank hole, running 5.54 SPM with 1575' of 7/8", 1475' of ¾", 1425' of 5/8", 200' of ¾" rods, a 2" pump, .399 psi/ft. tubing gradient, 1000 psi PIP, 100 psi WHP, and a 10 HP motor.

Figure 4 is the same plot as Figure 3 but plotted with True forces. Using Teff = True +PoAo and Po at depth = 100 +.399*4675 = 1965 psi. Then Teff = True (~849 from graph) +1965*3.14(.75^2)/4) ~0. This is the same case as in Figure 3 but plotted with the True Load on the load scale so that a part of the card sets below zero on the Y scale. If pump resistance should be input (perhaps 200 lbs.) then both Figure 3 and Figure 4 would have the bottom of the cards shifted downward with 200 lbs. of negative loading added to each. So what compressive loads cause buckling?

BUCKLING:

Table 1 shows the force to initiate buckling in a metal sucker rod is not a large force, especially for smaller diameter rods. So if one inputs 200 lbs. pump resistance into a predictive program (a common default) it would buckle any of the rod sizes in the table. This will show as a bottom card with 200 lbs. of the card below the zero line when plotting with Effective forces and will plot as PoAo + 200 below the zero line when plotting with True forces. However, once again the predictive will show negative Effective force (showing force that would buckle the rods) at the bottom of bottom rod only if input by the user or if a pump model is programmed into the model. Just buckling the rods may not be so bad but buckling with an appreciable side loading would be considered more of a problem. However continuous buckling causing wear due to rod slap could be a problem according to some operators.

What about up-hole buckling? Figure 5a is a case where pump friction is zero so there is no buckling at the pump, but there is buckling up the hole. Figure 5b shows that by slowing the well down the buckling tendency goes away. However, Figure 5c shows by adding 200 lbs. pump friction then there will be buckling at the pump, none up hole. Figure 5d is plot showing Effective and True loading in rods vs. depth showing up hole buckling of rods but no compression at the pump.

DELAYED SV OPENING:

Figures 3 and 4 showed incomplete fillage due to partial gas fillage of the barrel of the pump. There is another effect that can be exhibited by pumping gassy fluids. Figure 6a shows gas interference as opposed to fluid pound results in a gradual load release indicating high PIP as discussed above. The curved portion of the card on the left of the upstroke is caused by a delayed SV opening as the pump has to stroke upward to get the pressure below the TV to drop to the PIP. The same effect is seen with a leaky TV or a leaky plunger/barrel interface present. The delay, possibly due to gas below the TV and poor spacing and/or leaky pump on upstroke is shown in Figures 6b and 6c. This effect can be seen in actual diagnostic cards and also can be predicted by some predictive programs. A common way of gas appearing between the SV and the TV would be if oil with gas in solution is there as a pressure lowered then gas would evolve from solution.

SINKER BARS:

If one takes the case presented in Figures 3 and 4 and inputs 500 lbs. of pump friction then the buckling starts at 4254 ft., which is above the ¾” sinker rods. If one replaces the sinker rods by 200 ft. of 1 1/8” sinker bars then the buckling starts at 4535 ft., or in the sinker bars. So as one would suspect, heavier bars require less length. This type of approach to install sinker bars until the negative Effective negative loading is covered by sinker bars is used by operators. However, this requires the user to initially estimate the size and length of sinker bars unless the negative loading input can be carefully estimated by diagnostic results as discussed below. There are uncertainies with this approach as well.

There are sinker bar sizing routines based on the Z factor approach and the results seem reasonable. However, the Z factor calculation is based on an area seal of the ball in the seat whereas it is actually a line so results are somewhat arbitrary even though results often appear reasonable.

It is known from experience and statistics that sinker bars are useful to mitigate rod/tubing wear problems above the pump. What is not as well-known is what are the effects if slightly “too few” or “too many” sinker bars are used? Or to say it differently, what defines too many sinker bars? Another difficulty is that when adding sinker bars the region of negative loading may move upward requiring more bars than originally thought to cover negative loading and this effect is difficult to explain.

Also even if the rod load above the pump is zero (no resistance input) from above we see there can still be uphole compression and buckling and in this case as well you could add sinker bars to include the uphole negative loading. Uphole dynamic buckling can especially be aggravated by rod guides but even with no rod guides you can see uphole buckling predicted which could be changed by adjusting SPM for instance. If you do not get production you want from changing the design you might still apply guides to combat uphole compression and buckling

DIAGNOSTIC RESULTS:

The diagnostic program calculates the bottomhole card from a measured surface dynamometer card. Therefore, the surface card is fixed. The calculated bottom hole card is affected by the drag coefficients between the rods and tubing and the rods and fluid. Table 2 shows how input drag coefficients affect the dyno cards for the predictive and diagnostic wave equation models.

Because the drag coefficients affect the calculated bottom hole diagnostic card, this will be shown to give uncertainty when trying to determine if compression occurs. However, in some cases using different drag coefficients may help to fine tune the bottom card and get a better idea of what coefficients should be used. A measured or actual dyno card can be input into a diagnostic program using surface measurements, and then as energy is lost down the rod string, the bottomhole dyno card is calculated at the bottom of the rods. The bottom diagnostic card can be thought of as the measured surface card minus the energy, weight and dynamics lost along the rod string, and what is left over at the bottom of the rods is the bottomhole dyno card. Except for calculating production, the diameter of the downhole pump is not needed to calculate a bottomhole dyno card from a diagnostic program.

Figure 7 shows a bottomhole diagnostic card with drag coefficients (up/down) of .03 and .01. There is no input needed for the diagnostic fluid level as the diagnostic card fluid load is used to estimate the PIP in many cases. This card is plotted using Effective loads and shows about -246 lbs. compression for the drag coefficients used. But what if we change the coefficients?

Figure 8 shows a bottom hole card with a down stroke drag set to .135 and the Effective load on the down stroke is ~0 lbs., showing no tendency to buckle. So depending on the down stroke drag coefficient the card can either show no compression on the down stroke or it can show over 200 lbs. compression on the down stroke. Which is correct? Since the results are within reasonable ranges of the drag coefficient, the diagnostic program creates difficulties telling you if there is compression with the small down stroke coefficient or no compression with the larger down stroke coefficient unless exact drag coefficients are known. Exact values are not usually know. This may not be an optimum example, but it shows what can happen with indicated compression and the input down stroke drag coefficient/s. For the case of the larger coefficient the bottom load should not be above zero so it could be adjusted to zero (as above) to show no compression, but even so there still could actually be some down stroke compression. So this leads to some uncertainty for what is happening on the bottom hole card. The shape of the bottom hole card gives the most reliable information compared to taking exact numerical results from the bottom hole card. Also the numerical value of compression may be a small fraction of the fluid load in the bottom card so this also hinders interpretation. There are studies that focus on how programs calculate the bottomhole card, but most programs calculate similar results. Perhaps these studies should be better focused on predicting the drag coefficients used along the rods.

If proper values of drag coefficients can be determined, such as from frequent apparently reliable results across a field, then suitable results can still be inferred as in Figure 9. This figure shows a comparison of a measured downhole card (using special instrumentation) showing excellent agreement with diagnostic program results and measured data. These results were plotted with True forces and not Effective forces. However, if the drag coefficients are more uncertain then the above discussion still applies.

An indication that rod drag coefficients are too high or too low is the tip thickness on a gas cut card as shown by the following examples: Figure 10a shows too high of drag coefficients along rods; Figure 10b shows results with a higher drag coefficient; Figure 10c shows results with drag coefficients that are possibly correct; Figure 10d shows results with drag coefficients that are too low.

There is the same option with the diagnostic results as there was with the predictive results and that is whether or not to plot the bottom cards with True or Effective loads as already illustrated in the aforementioned figures. Figure 11 shows SCADA diagnostic cards plotted with both True (lower) and Effective (upper) loads. To convert the True card to the Effective card just add PoAo to the bottomhole loads as was done in one of the predictive examples.

Since there is some uncertainty in the bottom cards with the choice of drag coefficients affecting whether or not the bottom hole card shows compression or not and also how much fluid load is indicated, then what does the shape of the card indicate? Figure 12 shows a spike of compression on the down stroke at the end of the load release. This would be perhaps what one would expect for fluid pound where it can sometimes be explained by the plunger hitting the liquid to open the TV. Echometer has published some similar cards, but they were primarily for plugged intakes or low pressure situations in the pump. Most of the time one does not see the down spike of compression at the end of the load release even though fluid pound is suspected for low intake pressure gas cut cards.

Figure 13 shows when the TV opens vs where the fluid in the pump actually is at various intake pressures. It shows that for the very low intake pressure the TV opens about 3 inches before the plunger hits the fluid. However for the high intake pressure of 500 psi, the TV opens about 20 inches before the plunger hits the fluid. For the above plots liquid starts at zero. The load release distance is not a direct indication of how much gas is in the pump, especially if the intake pressure is high. Also this shows that the TV always opens before the plunger hits the fluid except for low intake pressures where it opens a small distance before the plunger encounters the fluid. You have more gas than you think in the pump by looking at the load release distance for high intake pressure.

The relationship for these type of results is as follows:
X is the distance from the end of the upstroke to the gas/liquid interface in the pump barrel
PIP is the intake pressure below the pump
Pd is the discharge pressure above the pump, psia
TVO is the distance from the end of the upstroke to where the TV opens
K is the ratio of Cp/Cv for the gas and is about 1.3 for natural gas.

The relationship that allows relating the distance to the fluid/gas interface and where the TV opens is:
$PIP\ X^k = Pd\ (X\text{-}TVO)^k$

This expression assumes isentropic compression of gas in the pump barrel.

Returning to low pressure gas cut cards and fluid pound, if there is no compression spike does rapid load release mean compression or does it mean fluid pound but no rod compression? So one is left with possible rod compression due to fluid pound perhaps only if one has the correct drag coefficients, but one doesn't know for sure what value for the down stroke should be used. One only knows that the bottom of the diagnostic card should not be more than zero, and that looking at the top load that one should not put in too high a value to concave the top load of the bottom card as this would seem unrealistic (after Echometer).

Fluid pound is conventionally said to occur for the low intake pressures where the load release occurs over a shorter time interval, but the shape of the card may not indicate rod buckling if no unusual compression is shown. Does fluid pound mean rod compression or does it mean shock wave when the load is quickly removed from the rods? The cards in Figure 13 do show gradual load release at high intake pressures and a rapid load release for low intake pressures.

What about the card in Figure 14? It shows a very large compression load as much or more than 2610 lbs. Are the rods experiencing a compression load of about 2610 lbs. above the pump, assuming the zero line is near the bottom of the fluid load and the card is plotted with Effective load? One would think if it were there would be a lot of destruction near the pump in the rods and tubing if loading were to be that high in rods and pull rods above the pump. In this case compression increases more as the plunger enters the barrel possibly with sand or iron sulfide along the barrel. The compression would appear lower if the down stroke drag factor was entered as a high value but still the slope would be there.

If the bottomhole card shows a large thickness or load it , again, could be due to drag coefficients being too low in the diagnostic program and leaving unaccounted for rod friction at the pump. Also this would make the bottom card showing bigger load and calculations of getting PIP=Pd-Fluid Load/(Pump Area) would show the PIP lower than it actually is. Another problem is that gas in the tubing creates a low Pd than most simple routines calculate.

Table 3 shows the maximum load on a rod under axial load before buckling that could be applied to a pump pull rod. One would think that if the compressive load on the pump is high and buckled the pull rod that pump destruction would possibly be near. Thus, this could be a table of possible upper limits of compressive loads that a pump could tolerate? If one suspects lower pump resistance then the vertical thickness of the bottom diagnostic card should be not too much more than the fluid load, where the max value would be from predictive results with low PIP.

FIELD SYMPTOMS:

Regardless of program outputs a double lipped failure as shown in Figure 15 is indicative of compression failures. When this occurs and the diagnostic program dyno card does not show the shape to indicate compression of loads, there is some kind of disconnect or the compression occurs intermittently and is not captured at the right time by the downhole card. However, shown above slight change in drag coefficients can lead to load enough to be the onset of compression and this can easily be overlooked. Also pump resistance could be intermittent with sand particles and slugs of iron sulfide, for example, passing through the pump causing rod compression at the pump on the downstroke.

SUMMARY AND CONCLUSIONS:

When a diagnostic bottom hole card appears normal but buckling is still suspected, a smaller downhole drag coefficient can give a bottom card showing some compression which could match field results if available.

1. Compression on bottom diagnostic card can appear as a spike at the end of load release, but this is not common.
2. The predictive program will show up hole buckling but usually only when there is very low intake pressure and perhaps higher SPM.
3. The predictive program will show no compression at the pump unless it is input. There is no model that shows what the force is when the plunger hits the fluid, but the TV is always open before the plunger hits the fluid (when gas is present in the pump). There are pump models that account for viscous drag between the plunger and barrel and flow of fluid up through the open TV but none are known that predict any impact loading as the plunger hits the liquid.
4. One can input a negative load or pump friction in the predicative program and then add sinker bars to cover the compression that was entered. This is arbitrary and would not be a lot different than just putting in some amount of sinker bars. Sinker bars seem to work well in operations. Adjusting the pump resistance in the predictive program to show compression could be less arbitrary if field symptoms or many diagnostic cards show what looks like actual rod compression the downstroke.
5. Other than a heavier rod string and being less flexible the definition of too many sinker bars is not well defined. Of course sinker bars in a curved section is not advised and sinker bars in a sandy environment may add to wear between the sinkers and tubing.
6. The TV always opens before the TV hits the fluid in the pump, especially for higher intake pressures. For the most part a compression spike at the end of the load release may be seen at for some very low intake pressure cards. Regardless fluid pound is thought in the industry to occur at low intake pressures when a quick load release in the rods above the pump occurs whether or not a compression spike shows on the bottom card.
7. Buckling with slight side loading may not be that harmful however there is the question of rod slap when buckling occurs. Buckling with higher side loading can obviously be a situation for more wear. Buckling of rods in the tubing could be a repeatable situation of pump resistance or intermittent if , for instance, sand particles come and go.
8. What causes pump resistance? Solids, scale, precipitates, crooked pump barrel, etc. can cause constant or intermittent pump resistance. Up hole dynamic buckling is predicted for low intake pressures and higher SPM. Field evidence of double lipped failures and excessive wear over the pump can be evidence of buckling. No anchor can cause rod/tubing wear above the pump and this is well known.

Bibliography:

1. Predicting the Behavior of Sucker Rod Systems, by S.E. Gibbs, SPE 588, April 4, 1988
2. Newman, K., Bhalla, K., “The Effective Force”, CTES L.C., Conroe, TX. Technical Note, Jan 13, 1999
3. Beam Pump Rod Buckling and Pump Leakage Considerations by: James C. Cox, Texas Tech University, H. Nickens, BP, J. Lea, Texas Tech University, SWPSC, April, 1998
4. Interpretation of Calculated Forces on Sucker Rods, by J Lea , P D Pattillo, and W R Studenmen, SPE Production and Facilities, Feb 1995
5. Update on Sandia Downhole Dynamometer Testing (Data Collected in 1996) by Lynn Rowlan, Echometer, Rod Pump ALRDC forum, Sept 17-20,2014

Size	W_{air}	W_{fluid}	Area	Lc	Fc
	Lb/ft	Lb/ft	in^2	Ft	(-)lbf
5	1.13	.9854	.307	23.16	22.82
6	1.63	1.42	.442	26.1	37.15
7	2.22	1.936	.601	28.96	56.07
8	2.9	2.528	.785	31.65	80.06
9	3.67	3.200	.994	34.26	109.6
10	4.53	3.950	1.227	36.74	145.1

Table 1: Loads to initiate buckling subject to certain restrictions.

		Predictive	Diagnostic
Cd, up	Higher	PPRL predicted higher	Peak of bottom card lower
Cd, down	Higher	MRPL predicted lower	Min of bottom card higher
Cd, up	Lower	PPRL predicted lower	Peak of bottom card higher
Cd, down	Lower	MRPL predicted higher	Min of bottom card lower

Table 2: Effects of drag coefficients on dyno cards.

COLUMN CRITICAL BUCKLING LOAD, LBS.

SIZE O.D. X I.D. IN.	FREE COLUMN LENGTH, INCHES																	
	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210
VALVE ROD																		
11/16"	2,442	1,563	1,085	797	610	482	390	322	271	231	200	173	152	135	120	108	97	88
7/8"	6,389	4,089	2,839	2,086	1,597	1,262	1,022	844	709	604	521	454	399	353	315	283	255	231
1-1/16"	13,890	8,890	6,173	4,535	3,472	2,743	2,220	1,836	1,543	1,315	1,133	987	868	796	685	615	555	503
PULL TUBE																		
533-C 15/16" X 5/8"	6,774	4,335	3,012	2,210	1,689	1,334	1,080	893	750	640	550	480	422	374	333	300	270	245
533-E 1-1/8" X 3/4"	13,388	8,966	6,227	4,574	3,502	2,767	2,241	1,852	1,556	1,326	1,143	996	875	775	690	620	560	508
232-K* 1-1/2" X 1-1/8"	24,592	21,028	16,671	12,317														

Table 3. Buckling limits for short rods that could be applied to pump pull rods.

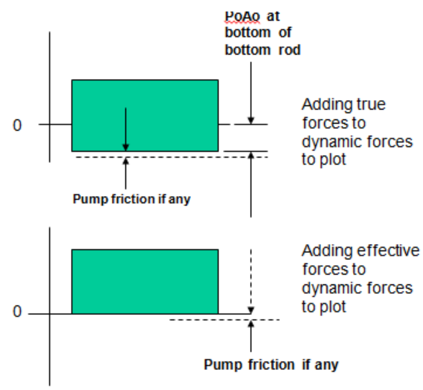

Figure 1: Contrast between plotting the same bottom card using True or Effective forces.

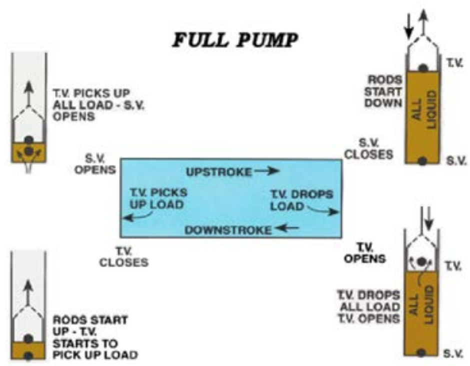

Figure 2a: Surface and bottom hole cards with complete pump fillage.

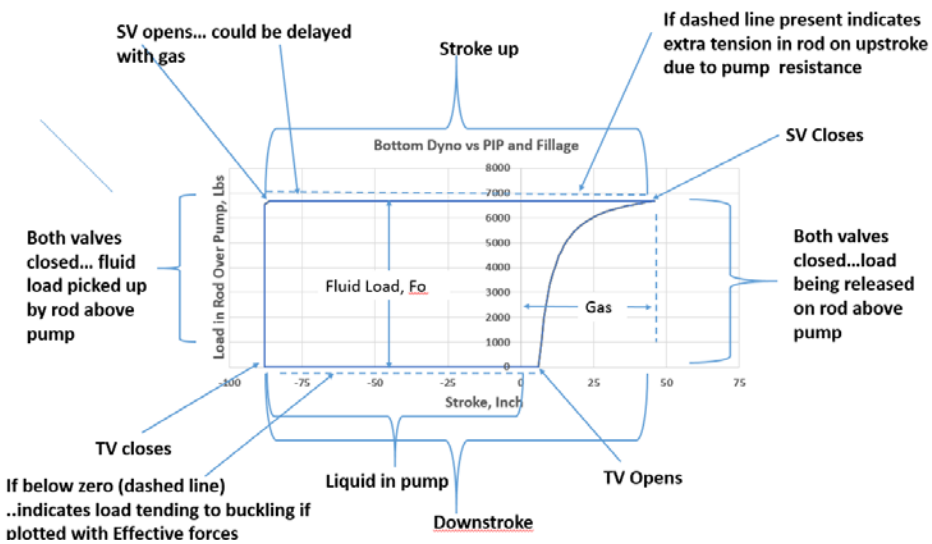

Figure 2b: Bottom hole card with incomplete pump fillage.

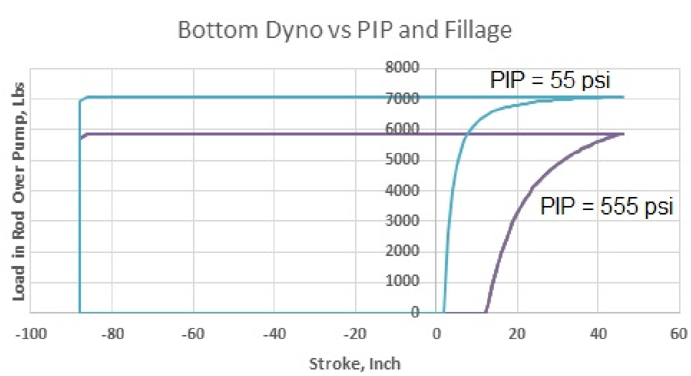

Figure 3: Predictive bottom cards with Effective Loads and no input pump resistance.

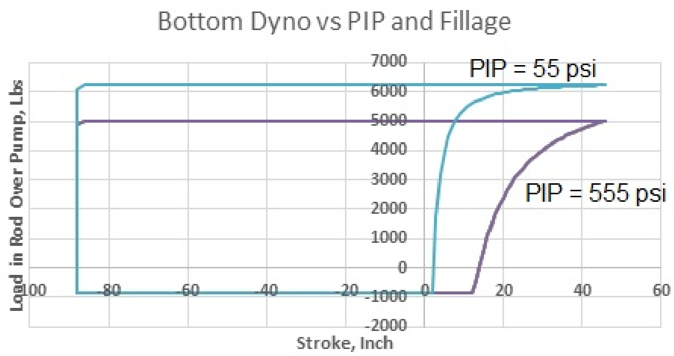

Figure 4: Same as Figure 3 but plotted with True forces.

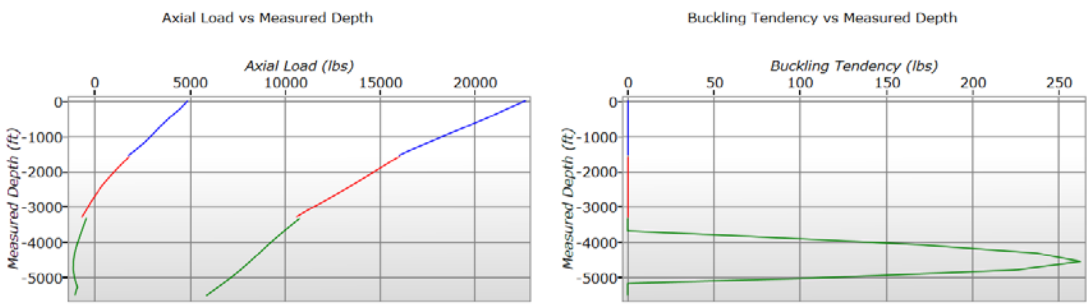

Figure 5a: Uphole buckling but no compression at the pump (GE SRod).

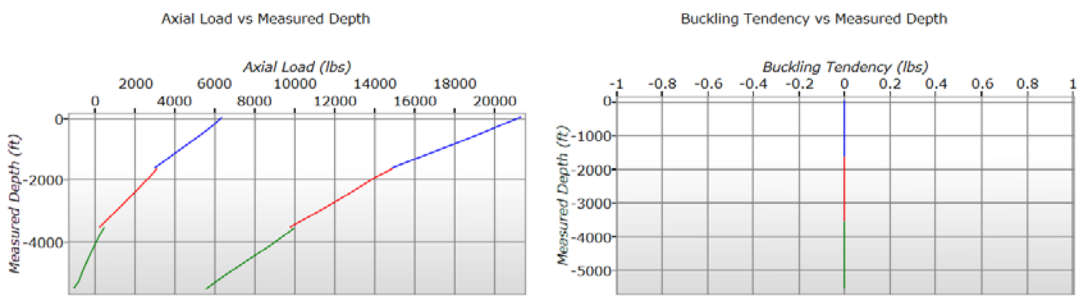

Figure 5b: No pump resistance input and no up hole buckling (SPM less than for Figure 5.a), (GE SRod).

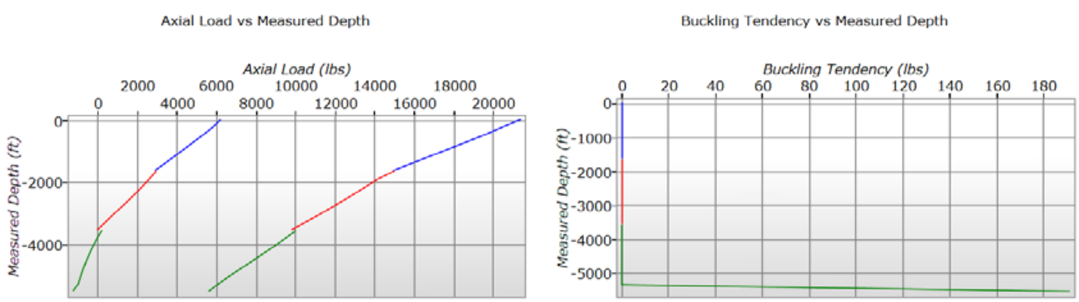

Figure 5c: No up-hole buckling but buckling indicated where pump resistance of 200 lbs. input (GE SRod).

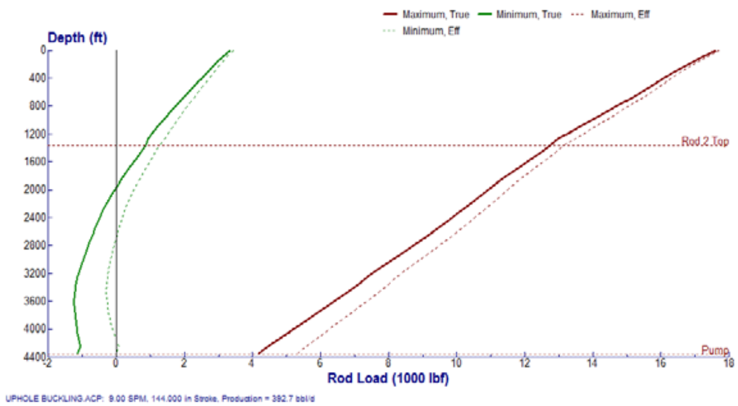

Figure 5d: Plot of Effective and True loading in rods from Cox, Nickens and Lea SWPSC, 2009, showing uphole negative effective loading (buckling).

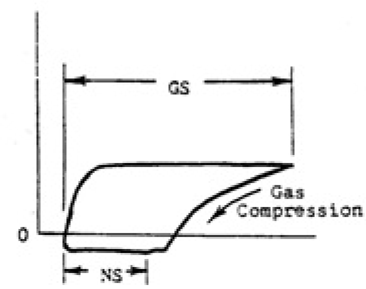

Figure 6a: Gas interference showing delayed SV opening.

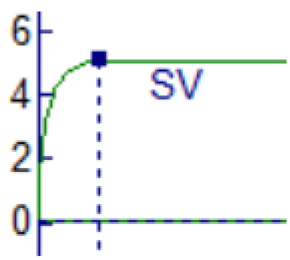

Figure 6b: Delayed SV opening with some gas below the TV with 5" of pump spacing.

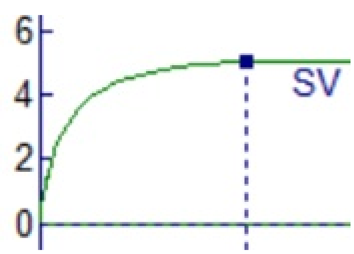

Figure 6c: Delayed SV opening with some gas below the TV with 15" of pump spacing.

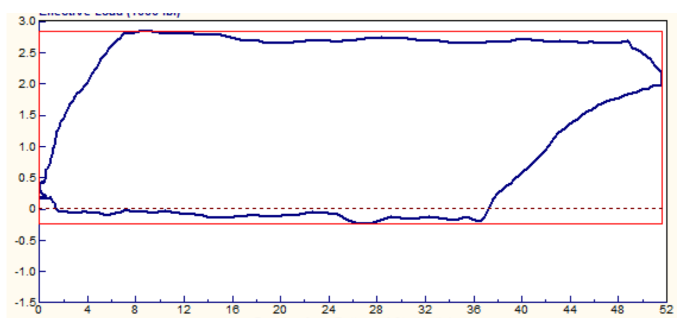

Figure 7: Diagnostic dyno card showing some compression on downstroke.

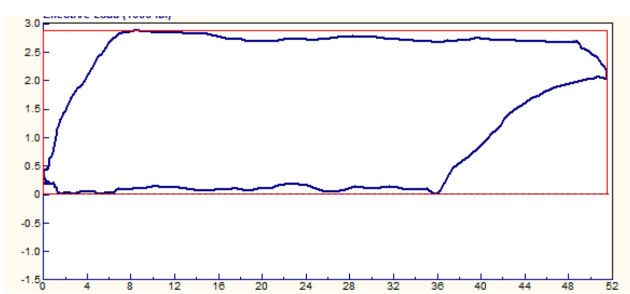

Figure 8: Diagnostic card showing no compression on downstroke.

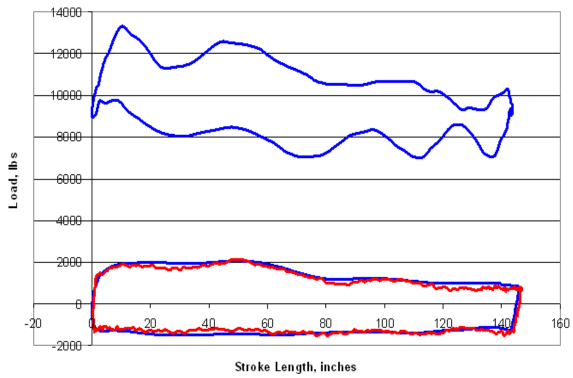

Figure 9: Good match of diagnostic program dyno card and measured dyno card.

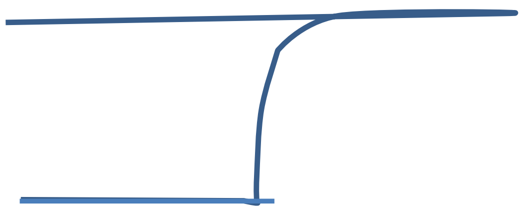

Figure 10a: Too high of drag coefficients.

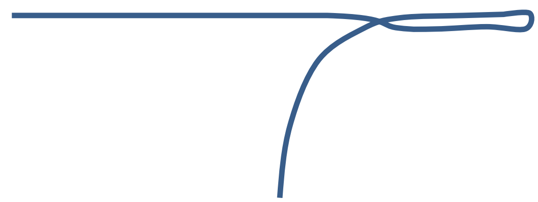

Figure 10b: Drag coefficients even higher

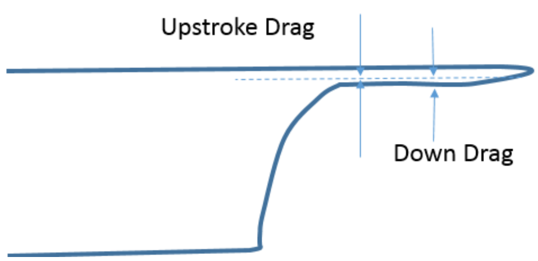

Figure10: Drag coefficients possibly correct.

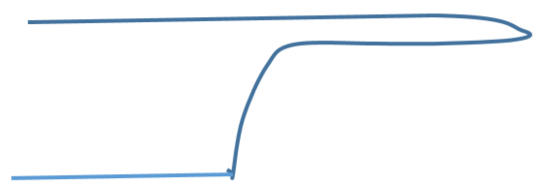

Figure 10d: Drag coefficients possibly too low.

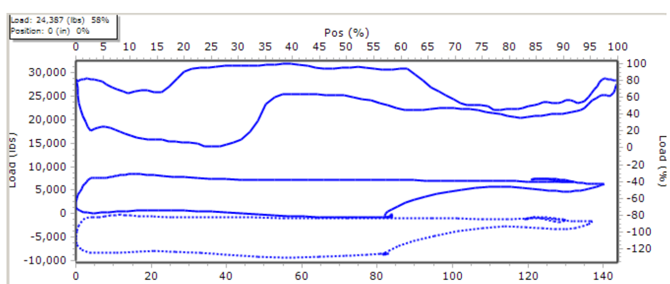

Figure 11: SCADA top and bottom hole diagnostic cards.

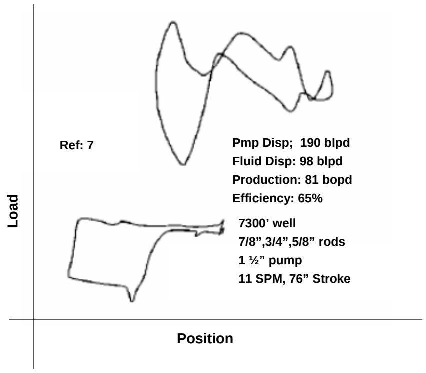

Figure 12: Compression spike.

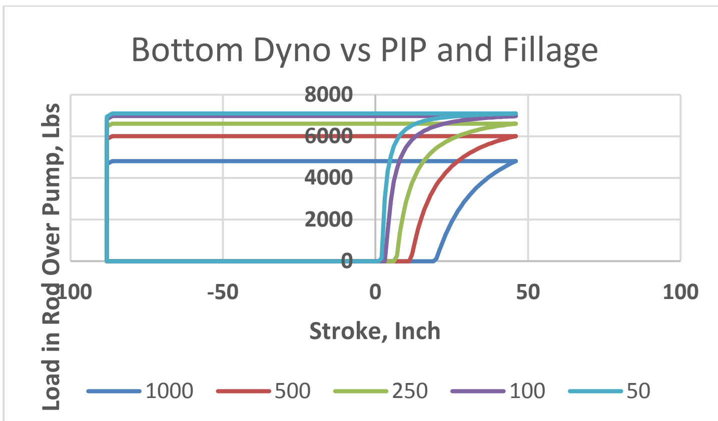

Figure 13: TV opening vs. fluid in pump at different intake pressures.

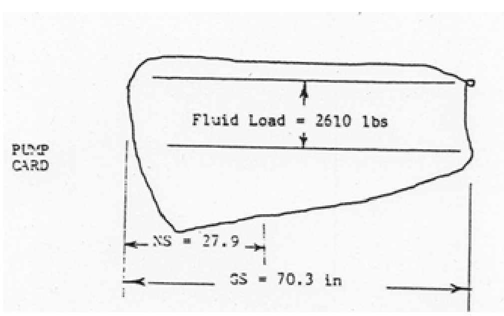

Figure 14: Bottom card with very high compressive load indicated.

Figure 15: Double lipped failure.

Appendix A: Calculation of True and Effective loads over Rod String.