A CURRENT COMPARISON OF SUCKER ROD STRING DESIGN PROGRAMS

Norman W. Hein, Jr., Consultant
Russell Stevens, Norris / A Dover Co.

ABSTRACT

A comparison was made between four commercially available sucker rod string design computer programs; Rod Star, S-Rod, Q-Rod, and LoadCal B, and a proprietary, modified API RP 11L based program. These programs used the same well design input parameters, where applicable, and their outputs were compared to the dynamometer cards taken representing the input conditions. The results show differences in the anticipated major design loads along with differences in the output information. Recommendations are made on potential changes to these programs and comments are made on some things to consider when these programs are used.

BACKGROUND

The design of sucker rod strings has evolved from the static analysis proposed by Slonneger[1], Mills[2] and Langer/Ianbergg[3] to the first analog computer model that considered dynamic effects. This later technique was accepted by the industry and adopted as API RP 11L[4].

A number of authors have refined the API rod string design modeling to extend this first order mathematical modeling to higher order wave equations, included dynamic and fluid friction effects, inclined/deviated and horizontal wells, and applied the modeling to personal computers.[5-24] These developments have extended the application of sucker rod string design programs, but, as with any design, the results from the program should be validated to assure accuracy in the estimated loads.

The validation of the program and the resulting design output parameters should be done for all wells since each well is normally different from other wells in the field. These differences can be different drilled depth, different production rates, different fluid gravity and percentages, different completions, etc. Additionally, when a sucker rod lift system is designed for a well, normally it is assumed that the pump setting depth is below the lowest perforated zone, the fluid level is pumped down to the setting depth, and the heaviest specific gravity fluid at the maximum production rate from the well will be lifted to the surface.[25] While these extreme design assumptions allows sizing equipment that should be assured to meet the production requirements for an extended lifetime of the well, they do not and should not represent the actual operating conditions for the well.

It is recommended that along with the suite of dynamometer cards that represent stable production conditions after installing and pumping down the fluid level in a well, these operating conditions/parameters should be input to the design program to check and validate the original design assumptions.[26] This also allows "good" operating conditions to be obtained and the loads compared to the design to see if the assumptions are correct or if adjustments need to be made in the assumptions to match the actual well conditions and the loads.

WELL DESIGN PARAMETERS

Three different wells located in different West Texas fields were used for evaluation of design versus actual well loads. Table I presents the different well design parameters and the data from these wells. Well 3 had three different operating conditions included since it included the addition of downhole sinker bars located directly above the downhole sucker rod pump. The first condition (3A) was the well as originally operated without sinker bars. The second condition (3B) included 38 feet of 1.25-inch sinker bars. While most of the downhole conditions and depths were the same, the operating fluid level was approximately 120 ft. lower. This lower fluid level should require more work by the lift system and, therefore, should increase the loads on the rods. However, if the assumed advantages of sinker bars actually were effective in raising the minimum polished rod load without increasing the peak polished rod load, then there may be a trade-off of increased workloads and the decreased dynamic effect loads. The 3C conditions were run using the same fluid level as the 3B condition but sinker bars were not included. These new "before and after" sinker bar additions were included to provide another opportunity to see if these programs can accurately predict the dynamic effects of bars since it was previously reported that design programs available in the mid 1990's did not.[27]

Surface dynamometer cards were obtained from these three wells with the representative operating conditions, except for condition 3C. A calibrated Johnson-Fagg dynamometer was used for each well case. The representative card major loads were obtained to compare the design output to the appropriate measured load.

DESIGN PROGRAMS

Four commercially available sucker rod string design programs were used for the comparisons. These included:

- Load Cal B (available from Lufkin),
- Q Rod (available from Echometer),
- Rod Star (available from Theta Enterprises), and
- S Rod (available from Lufkin Automation).

An additional, proprietary, modified API RP11L program also was used. This program is limited to designing and analyzing only steel rod strings for API accepted pumping units. The other programs are capable of designing and analyzing these conditions plus they advertise they can include effects of sinker bars. These programs also have varied capabilities. They can include fiberglass rod strings. Some include other than API accepted pumping units. Some can also include design effects for deviated wells and fluid friction. However, not all programs provide design output of major loads or design parameters. These differences will be discussed further.

DESIGN OUTPUT RESULTS

Tables II to VI present the results of the major design outputs from the five computer programs. It should be noted that they are listed as generic program A to E and are not correlated to the above list of programs. Comparing the results for each well condition, it is shown that not all programs provide the estimated weight of the rods in fluid (which is identical to the standing valve (SV) load for the entered operating conditions). Also, not all programs provide the estimated traveling valve (TV) load.

Two programs provide the fluid load over the gross plunger area (Fo; according to API RP 11L nomenclature). However, this load is not very useful without the SV load. One program provides the SV load and Fo. This would allow the TV load to be obtained, but a separate addition has to be done outside the design program by adding the SV load to the Fo load.

Three of the five programs provided an estimate of the pump displacement assuming a volumetric efficiency of 1.0. While this is not the expected operating condition, it should provide an estimate of the expected maximum production from the well with higher fluid level and a full pump condition.

Three of the programs provide the major non-dimensional pumping parameters of N/No' and Fo/SKr. These non-dimensional loads are described in API RP 11L but represent the speed and load factors for design. While some programs may limit the non-dimensional speed or recommend a maximum of 0.35, most programs provide no discussion if this speed is exceeded. This also is true for the non-dimensional load parameter. Normally it is recommended to design for a maximum of 0.5 for steel rod strings. However, most programs do not provide warnings if this parameter is exceeded.

DYNAMOMETER CARDS AND COMPARISONS

Figure 1 to 4 provide the surface dynamometer cards from the three wells including well condition 3A with out sinker bars and 3B after sinker bars are added. It should be noted that these renditions of the actual cards might not exactly provide the same loads if the load and length constants are used to remeasure the cards. This is probably due to changes from the original card traces from scanning and/or from printing.

The five major surface dynamometer loads from each card condition was measured from the original card and are shown in the appropriate column in the comparison tables. These major loads to determine operating conditions and comparing to design are the:

- Standing valve (SV) load,
- Traveling valve (TV) load,
- Peak polished rod load (PPRL),
- Minimum polished rod load (MPRL), and
- Resulting maximum rod stress.

This stress assumed using the peak polished rod load divided by the cross-sectional area of the top rod in the rod string.

Tables VII to XI shows the results of the various program output estimated loads to the compared to the appropriate major dynamometer card load. The Difference in each program is shown as a percentage found by dividing the appropriate design load by the actual well dynamometer card load.

Note that this comparison assumes:

- The dynamometer card loads were accurately measured and obtained from the cards, and
- The well design conditions accuracy reflected the actual well conditions (fluid level, specific gravity of the mixed fluid, correct rod string section lengths, etc).

Results for each well condition magnify the problems with the design programs that do not provide all the necessary output loads for comparison to the dynamometer cards. Thus, it becomes difficult to troubleshoot problem wells and then trying to optimize or prevent future failures. While some may say these loads are not important if pump cards are interpreted, it raises the issue if the design program can accurately translate the surface rod loads through the program to obtain the necessary downhole loads and related pump card shape.

Comparing the results from the percentage variation for each well, design program E appears to more accurately estimate the SV and TV load. The difference, especially in the SV load is peculiar since this should be a simple calculation taking the weight of the rods in air and subtracting the buoyancy of these rods. It is even more peculiar that program E came closer to calculating the measured SV load for condition 3B, even though it does not currently include sinker bar effects.

Comparing the PPRL (and related maximum rod stress) it does not appear that one program is more accurate than another. The accuracy of estimating the MPRL is much worse than PPRL for all programs. Again, not one program is better than another. Additionally, no program properly estimated that the operating condition for wells 2 and 3A would be dramatically affected by the dynamic conditions in the wells. However, program D was the best for estimating the effects of sinker bars for well condition 3B.

It should be noted that the design output for well condition 3 called out that three programs noted that the top rod in the rod string design would require slimhole rod couplings to be run for the 2.5" production tubing. Two of the programs did not provide this catch in operating requirements. Additionally when the maximum rod stresses were compared, it appeared that program E had stresses much higher than the other programs. This may have been due to the slimhole coupling derating factor this program automatically includes that the other programs do not apparently include.

Other comparisons of slimhole designs were recently presented and discussed at the 2004 Permian Basin Artificial Lift and Production Operations Forum, Midland, Texas. During the discussion, it was noted that some did not know that the API Standardization Committee considered the original work by Gipson and Swaim[28] and the refinement by Hermanson[29] and accepted these final derating factors published in the 1987 edition of the Petroleum Engineering Handbook. These factors are reproduced in Table XII.

CONCLUSIONS

1. Not all sucker rod string design programs provide the five major surface loads nor the two major non-dimensional operating parameters as output for their programs.
2. Not all programs provided checks on slimhole coupling required use.
3. Only one program included slimhole coupling derating factors in the allowable rod stress/load.
4. Variations in those programs that did provide a SV load output is peculiar since this load should be identical, if the programs assumed the same specific gravity fluids, the same rod string, and weights of rods.
5. There were variations in all programs on the PPRL and wider variations on the MPRL.
6. No program accurately predicted the static rod, valve, peak or minimum loads when sinker bars where installed.
7. Sinker bars were effective in raising the minimum load without increasing the peak polished rod load.
8. Variations in accurately predicting rod loads, especially peak load, may effect the resulting equipment selection, since if conservative estimates are obtained, larger, more expensive equipment may be selected for an installation.
9. Sucker rod string design programs should be run on all wells, as soon as possible after reaching static operating conditions, to compare design versus installed conditions. This will allow adjustments to be made in the program to better match actual well conditions.

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Table I
Rod String Design Program Conditions
INPUT Well Data

Parameter	**Well No. 1**	**Well No. 2**	**Well No. 3A**	**Well No.3B**	**Well No. 3C**
Fluid Level (ft)	2023	3750	2636	2759	2759
Pump Depth (ft)	4500	3807	3429	3429	3429
Anchor Depth (ft)	4500	3687	3158	3158	3158
Stroke Length (in)	52	96	168	168	168
Speed (spm)	8.22	13	9.8	9.8	9.8
Tubing Dia. (in.)	2.375	2.875	2.875	2.875	2.875
Pump Dia. (in.)	1.25	2.25	2.25	2.25	2.25
Mixed gravity (G)	1.00	0.961	1.00	1.00	1.00
Tubing Press. (psi)	49	65	60	60	60
Casing Press. (psi)	49	0	25	25	25
Pumping Unit Size	C114-143-64	C320-300-96	A912-305-168	A912-305-168	A912-305-168
Unit Rotation	cw	cw	Cw	cw	cw
Rod String No.	66	76	86	86	86
88 (feet)	0	0	1104	1116	1116
77 (feet)	0	1557	1250	1250	1250
66 (feet)	4500	2250	1075	1025	1063
Rod Grade	C	C	C	C	C
Sinker Bars (ft)	n/a	n/a	n/a	38 (1.25")	n/a

Table II
Design Program Output Results for Well 1

Parameter	Program A	Program B	Program C	Program D	Program E
Wrf =SVL (lb)		6,604		6,499	6,406
TVL (lb)		Fo=1,075	Fo=1,300		7,480
PPRL (lb)	9,441	9,046	9,100	8,659	8,619
MPRL (lb)	4,865	5,396	5,400	5,375	5,678
PT (M in-lb)	71.2	51	67	60.7	51.9
HPpr	2.5	2.2	2	1.5	1.5
PD (ve=1.0) (bpd)	70			73	74
Net PD (ve=80) (bpd)	55	59	59	59	52 (70%)
Max Rod Stress (psi)	21,145	20,249		19,600	19,510
% Allowable	56.0	46.0	70.0	43.3	55.0
N/No'		0.151		0.151	0.151
Fo/SKr		0.082		0.087	0.082
NOTES/Comments					

Table III
Design Program Output Results for Well 2

Parameter	Program A	Program B	Program C	Program D	Program E
Wrf =SVL (lb)		6,479		6,470	6,365
TVL (lb)		Fo=6,463	Fo=6,400		12,568
PPRL (lb)	18,051	17,346	17,300	17,300	16,798
MPRL (lb)	1,291	1,650	1,300	2,744	2,681
PT (M in-lb)	415.9	435	456	389.10	381.7
HPpr	25.1	25.5	23	21.5	20.6
PD (ve=1.0) (bpd)	668			647	646
Net PD (ve=80) (bpd)	533	559	525	518	452 (70%)
Max Rod Stress (psi)	29,853	28,681		28,769	27,936
% Allowable	128/134	121/118	121	118	101
N/No'		0.187		0.184	0.124
Fo/SKr		0.194		0.198	0.129
NOTES/Comments	%Reducer 130	Gearbox 136%			Rod stress out of limits

Table IV
Design Program Output Results for Well Condition 3A

Parameter	**Program A**	**Program B**	**Program C**	**Program D**	**Program E**
Wrf =SVL (lb)		7,010		7,023	6,916
TVL (lb)		Fo=4,882	Fo=5,000		11,454
PPRL (lb)	16,876	15,309	17,000	15,658	17,271
MPRL (lb)	1,014	1,410	1,700	1,682	3,348
PT (M in-lb)	490.4	570	498	551.7	489.3
HPpr	29.9	31.3	29	24.5	27.2
PD (ve=1.0) (bpd)	908			929	926
Net PD (ve=80) (bpd)	725	760	732	743	648 (70%)
Max Rod Stress (psi)	21,359	19,365		19,937	21,990
% Allowable	91/88/83	81/78/77	91	83%	78.5
N/No'		0.122		0.119	0.119
Fo/SKr		0.068		0.063	0.061
NOTES/Comments	Req'd slimhole couplings	Req'd slimhole couplings			Slimhole req

Table V
Design Program Output Results for Well Condition 3B (w/ 38 ft. of sinker bars)

Parameter	**Program A**	**Program B**	**Program C**	**Program D**	**Program E**
Wrf =SVL (lb)		7,120		6,967	6,916
TVL (lb)		Fo=5,062	Fo=5,000		11,665
PPRL (lb)	17,328	15,692	17,100	15,643	17,490
MPRL (lb)	977	1,411	1,900	1,582	3,348
PT (M in-lb)	507	582	498	553	494.7
HPpr	31	31.9	29	24.6	27.9
PD (ve=1.0) (bpd)	915			929	924
Net PD (ve=80) (bpd)	731	758	732	743	647
Max Rod Stress (psi)	21,935	19,852		19,917	27,988
% Allowable	94/91/86/22	83/82/81/47	92	83	79.6
N/No'		0.121		0.118	0.119
Fo/SKr		0.069		0.063	0.064
NOTES/Comments	req slimhole	req slimhole			**Not do bars**

Table VI
Design Program Output Results for same 3B FL w/o bars

Parameter	**Program A**	**Program B**	**Program C**	**Program D**	**Program E**
Wrf ≥SVL (lb)		7,023		7,023	6,916
TVL (lb)		Fo=5,062			11,665
PPRL (lb)	17,190	15,561		15,924	17,490
MPRL (lb)	952	1,319		1,569	3,348
PT (M in-lb)	501.8	586		567.8	494.7
HPpr	30.9	32		25.4	27.9
PD (ve=1.0) (bpd)	913			926	924
Net PD (ve=80) (bpd)	729	758		748	647
Max Rod Stress (psi)	21,759	19,686		20,274	27,988
% Allowable	93/90/86	82/80/79		85%	79.6
N/No'		0.122		0.118	0.119
Fo/SKr		0.07		0.063	0.064
NOTES/Comments	req slimhole	Req slimhole			req slimhole

Table VII
Dynamometer Comparison to Design Program for Well 1

Parameter	*Dynamometer*	**Diff. A**	**Diff. B**	**Diff. C**	**Diff D**	**Diff. E**
Wrf ≥SVL (lb)	**6,375**		103.59%		101.95%	100.49%
TVL (lb)	**6,910**		111.13%			108.25%
PPRL (lb)	**8,900**	106.08%	101.64%	102.25%	97.29%	96.84%
MPRL (lb)	**5,760**	84.46%	93.68%	93.75%	93.32%	98.58%
Max Rod Stress (psi)	**20,100**	105.20%	100.74%		97.51%	97.06%

Table VIII
Dynamometer Comparison to Design Program for Well 2

Parameter	*Dynamometer*	**Diff. A**	**Diff. B**	**Diff. C**	**Diff. D**	**Diff. E**
Wrf ≥SVL (lb)	**6,379**		101.57%		101.43%	99.78%
TVL (lb)	**12,054**		107.37%			104.26%
PPRL (lb)	**18,443**	97.87%	94.05%	93.80%	93.80%	91.08%
MPRL (lb)	**351**	367.81%	470.09%	370.37%	781.77%	763.82%
Max Rod Stress (psi)	**30,687**	97.28%	93.46%		93.75%	91.04%

Table IX
Dynamometer Comparison to Design Program for Well Condition 3A

Parameter	***Dynamometer***	**Diff. A**	**Diff. B**	**Diff. C**	**Diff. D**	**Diff. E**
Wrf =SVL (lb)	**5,244**		133.68%		133.92%	131.88%
TVL (lb)	**12,678**		93.80%			90.35%
PPRL (lb)	**19,152**	88.12%	79.93%	88.76%	81.76%	90.18%
MPRL (lb)	**0**					
Max Rod Stress (psi)	**24,397**	87.55%	79.37%		81.72%	90.13%

Table X
Dynamometer Comparison to Design Program for Well Condition 3B

Parameter	***Dynamometer***	**Diff. A**	**Diff. B**	**Diff. C**	**Diff. D**	**Diff. E**
Wrf =SVL (lb)	**6,612**		107.68%		105.37%	104.60%
TVL (lb)	**10,716**		113.68%			108.86%
PPRL (lb)	**16,416**	105.56%	95.59%	104.17%	95.29%	106.54%
MPRL (lb)	**1,595**	61.25%	88.46%	119.12%	99.18%	109.91%
Max Rod Stress (psi)	**20,912**	104.89%	94.93%		95.24%	133.84%
						NOT DO BARS

Table XI
Dynamometer Comparison to Design Program for Well Condition 3C

Parameter	***Dynamometer***	**Diff. A**	**Diff. B**	**Diff. C**	**Diff. D**	**Diff. E**
Wrf =SVL (lb)	**6,612**		106.22%		106.22%	104.60%
TVL (lb)	**10,716**		112.78%			108.86%
PPRL (lb)	**16,416**	104.71%	94.79%		97.00%	106.54%
MPRL (lb)	**1,595**	59.69%	82.70%		98.37%	109.91%
Max Rod Stress (psi)	**20,912**	104.05%	94.14%		96.95%	133.84%

Table XII
API Recommended Derating Factors for Maximum Allowable Load or Stress for Slimhole Couplings for Various Rod Sizes and Grades

API Rod Size (in.)	API Grade K	API Grade C	API Grade D
⅝	—	0.97	0.77
¾	—	—	0.86
⅞	0.93	0.88	0.69
1	—	—	0.89

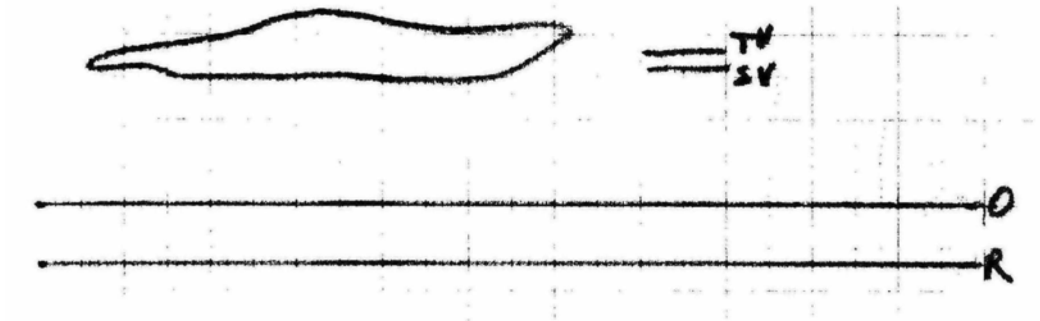

Figure 1 - Well 1 Surface Dynamometer Card (1” = 7675 lbs)

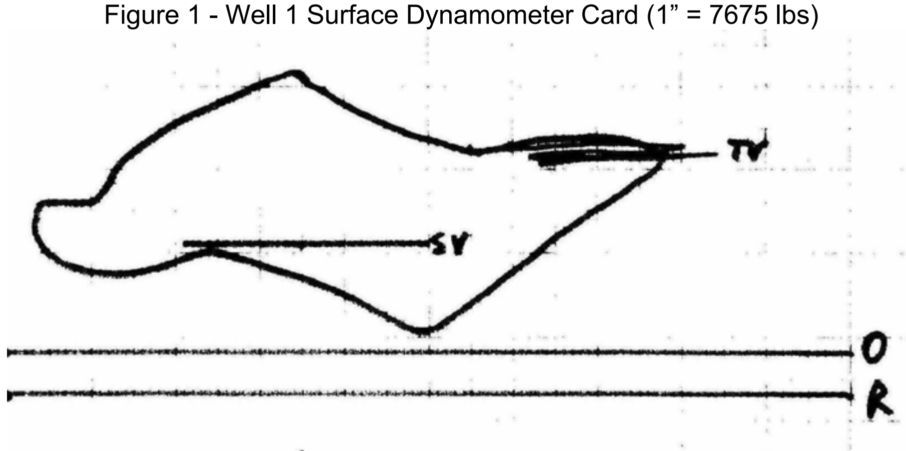

Figure 2 - Well 2 Surface Dynamometer Card (1”= 11,350 lbs)

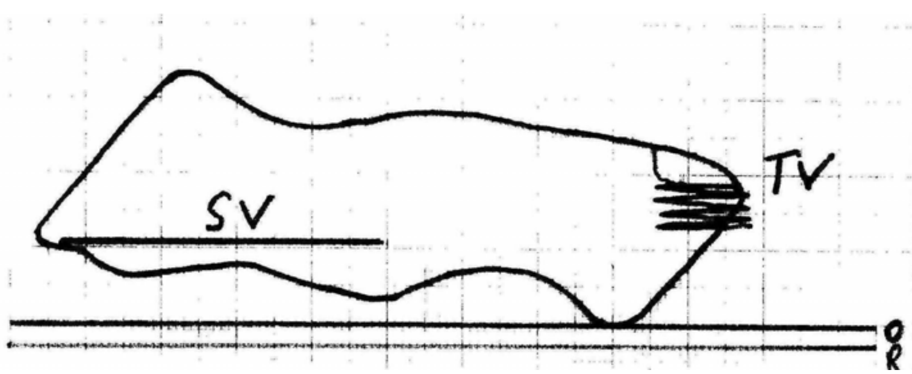

Figure 3 - Well 3A Surface Dynamometer Card
Note load trace touches 0 lb. Load line. (1” = 11,400 lbs.)

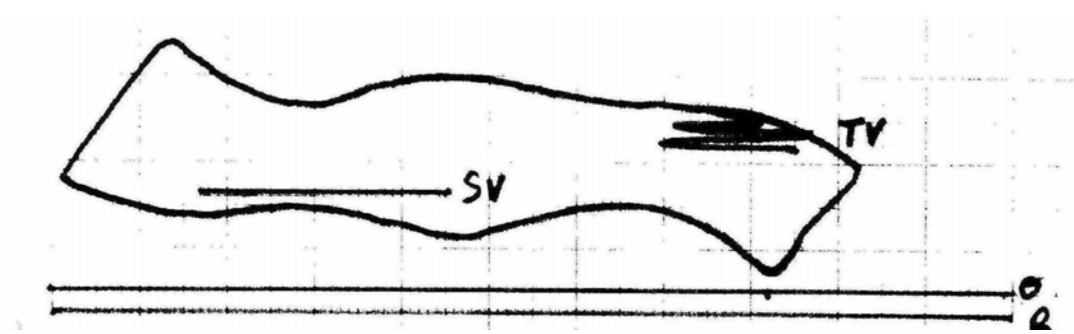

Figure 4 - Well 3B Surface Dynamometer Card After Addition Of 38 ft. 1.24” Sinker Bars
Note MPRL above 0 line and PPRL has decreased. (1” = 11, 400 lbs.)