ROD STRESSES FROM RP11L CALCULATIONS

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ABSTRACT: Current API RP11L rod taper percentages are based on empirical formulas which were used to simplify the system calculations so that they could be made manually. The trend toward deeper, high volume pumping has resulted in higher rod loads and stresses so more accurate taper percentages are needed. The availability of the personal computer now makes it possible to design accurate rod tapers for each individual well. This paper presents a method for the determination of rod stresses in the intermediate tapers of the rod string and an improved criteria for taper design.

ROD STRESSES FROM RP11L CALCULATIONS

In March, 1976, Buford Neely, Shell, in a Petroleum Engineer article[1], offered a program and a method by which the rod taper percentages, based on equal "modified stresses", could be calculated.

He defined modified stress as follows: "When a maximum and minimum stress have been calculated or measured on a sucker rod during a pumping cycle, the modified stress is the stress level that would give equivalent loading if the minimum stress during the pumping cycle were zero". The following formula is used to calculate this "modified stress".

$$S_{mod} = S_{max} - 0.5625\ S_{min}$$

He cites as an example: A rod would be equally loaded if it had a maximum rod stress of 25,000 psi and a zero minimum stress or if it had a maximum rod stress of 35,000 psi and a minimum rod stress of 18,000 psi.

The program used the following method. After determining what the dynamic loads were, they were assigned in proportion to rod taper length to each taper. An empirical formula was used to determine the maximum value of the dynamic forces at the surface. This force was assumed to diminish in proportion to depth. This empirically calculated dynamic force was a function of pumping speed, fluid load, spring constant, and stroke length. To find some typical values to use, rather than calculate each case, he suggested using a N/No' value of 0.35 and typical depths and stroke lengths which fit the common operating practice of that era. Tapers were then calculated which had equal "modified" stress for these conditions.

In 1977, the American Petroleum Institute adopted the rod string design method proposed by Neely, and included rod percentages calculated by this procedure in the latest edition of RP11L[2]. The tables published in RP11L gained wide acceptance. Thousands of rod strings, using these recommended taper lengths, have since been installed.

The use of the API taper lengths saves the time of a detailed string design, but the wide availability of personal computers today has eliminated the need to resort to such a shortcut method. A proper rod string design, with equal fatigue endurance ratings, should be based on the actual pumping speed, stroke length, pump setting depth and plunger size.

The basic assumptions used by Neely, and used but not shown in the API RP11L, to arrive at the published taper lengths were:

Largest Rod Size	N/No'	String Length	Stroke Length	Approx. SPM
< 3/4"	0.35	4000	54	23.7
3/4"	0.35	4000	54	23.7
7/8"	0.35	8000	120	11.6
1"	0.35	8000	120	11.6
1 1/8	0.35	12000	192	8.8
1 1/4	0.35	12000	192	8.8

Rod designs for operating conditions which are different than the above may require taper percentages which are significantly different than those listed in API RP11L. Refer to Figures. 1 and 2. These figures show designs for 1 1/4" and 1 1/2" pumps with 76 and 86 rod strings at 3,000', 6000', and 9000' with pumping speeds of 6, 10 and 14 strokes per minute. The taper percentages shown are those which would have been calculated if the Neely program had been used to calculate the tapers individually. They are compared with the recommended taper percentages from the API RP 11L.

These charts are shown to make the point that even with Neely's original program, the rod taper balances would have been better if a specific calculation had been made for each well. Observe that the deeper rod strings, which are the most susceptible to failure, depart the most from the present API recommended tapers.

No recent work has been done on this subject, but with the availability of PC computers it is now possible to calculate the best taper for each operating condition.

The RP11L calculations only give loads at the polished rod and do not give loads at any other point in the string. A typical API RP11L calculation is shown in Exhibit #1. The loads which make up the polished rod loads can be visualized by referring to Fig. 3[3]. The peak load consists of the weight of rods in fluid + the fluid load + the dynamic load. The minimum load consists of the weight of rods in fluid minus the dynamic load.

The total upstroke dynamic load can be determined by subtracting the weight of rods in fluid (Wrf) plus the fluid load (Fo) from the peak polished rod load (PPRL).

Dynamic load is proportional to the weight of the rod string rather than the length of the rod string. The formula F = Ma shows that, with the same acceleration, a larger mass will result in a larger force. Therefore a 6000' string of 1" rods would have a bigger dynamic load than the same length of 5/8" rods.

Refer to Fig. 4. An examination of the hydralics and dynamics shows that the load at the top of the 3/4" taper consists of: the total weight rods in air (W) + the load carried by the net plunger area ($AREA_{plunger} - AREA_{bottom\ rod}$) + the percentage (by weight) of total dynamics - the pump intake pressure times the gross plunger area.

$$PPRL_{3/4} = W_{air3/4} + [0.433 \times G \times L \times (A_p - A_{br})] + [DYN_{total} \times W_{3/4} / W_{total}] - [0.433 \times G \times (L - H) \times Ap]$$

The load at the top of the 7/8" taper consists of: the load at the top 3/4" rod + the weight of the 7/8" rods in air + the percentage (by weight) of the total dynamics for the 7/8" - the buoyancy of the net area between the 7/8" rod and the 3/4" rod.

$$PPRL_{7/8} = PPRL_{3/4} + W_{air7/8} + [DYN_{total} \times W_{7/8} / W_{total}] - [0.433 \times G \times L_{7/8} \times (A_{7/8} - A_{3/4})]$$

In a two way taper the $PPRL_{7/8}$ is the same as that calculated by the RP11L method. With more tapers the above formula would just be extended to the next taper.

Refer again to Fig. 3. The downstroke minimum load consists of the weight of rods in fluid - the downstroke dynamics.

The total downstroke dynamics can be found by subtracting the minimum load from the buoyant weight of the rods.

Refer to Fig. 4A. An examination of the hydralics and dynamics shows that the downstroke load on the top rod in the 3/4" taper is: weight of the 3/4" rods in air - the percentage (by weight) of the total downstroke dynamics - pressure at the bottom rod (pump) times the area of the bottom rod (total buoyant effect on the area of the bottom rod).

$$MPRL_{3/4} = W_{air3/4} - [DYN_{total} \times W_{3/4} / W_{total}] - [0.433 \times G \times L \times AREA_{3/4}]$$

And the minimum polished rod load on the top of the 7/8" taper would be: the minimum polished rod at the top 3/4" rod + the weight of the 7/8" taper in air - proportional downstroke dynamics - the buoyancy of the net area between the 7/8" rod and the 3/4" rod.

$$MPRL_{7/8} = MPRL_{3/4} + W_{air7/8} - [DYN_{total} \times W_{7/8} / W_{total}] - [0.433 \times G \times L_{7/8} \times (AREA_{7/8} - AREA_{3/4})]$$

In a two way taper the $MPRL_{7/8}$ is the same as that calculated by the RP11L method. With more tapers the above formula would just be extended to the next taper.

In the API 11BR[4], Recommended Practice for Care and Handling of Sucker Rods, a "Modified Goodman Diagram" is presented which defines the allowable stress ranges for sucker rods. It defines the allowable range of stress on a sucker rod as:

$$Sa = S.F. \times ((0.25 \times T) + (0.5625 \times Smin)$$

where:

SF = Service Factor
Sa = Allowable Stress, psi
T = Maximum Tensile Strength, psi
Smin = Minimum Stress, psi

Since the Service Factor defines the actual stress as a percentage of the allowable stress, it is the most precise way to compare the relative loading of each taper in the rod string. Designing for Equal Service Factors at the top of each taper will give rod tapers based on equal service life.

Once the PPRL and MPRL have been calculated, the API Modified Goodman Diagram formula can be used to determine the Allowable Stress. The Service Factor is the ratio of the Actual Stress to the Allowable Stress, so equal Service Factors will have equal fatigue endurance.

Figure 5 and Figure 6 show taper designs using this Equal Service Factor method for the same operating conditions as were used in the comparison of API percentages vs the Neely design method. These are: 1 1/4" and 1 1/2" pumps with 76 and 86 rod strings at 3,000', 6000', and 9000' with pumping speeds of 6, 10 and 14 strokes per minute.

These figures illustrate that specific calculations for each operating condition is most desirable. They also show that the API percentages, for the operating conditions examined, give the top rods in the string a larger percent than good design practice would dictate. This results in a poorer Service Factor and makes the top rods the most likely to fail. In addition, a greater percent of large rods in the string adversely affects the peak polished rod load and increases the energy requirements. In deep wells, failures in the top rod may cause damage to the lower sections of the rod string.

Conclusions:

The Equal Service Factor method is a better way to calculate rod tapers. Personal computers have eliminated the need for the use of simplifying assumptions in taper design and permit a more precise calculation of the optimum tapers for each operating condition.

REFERENCES

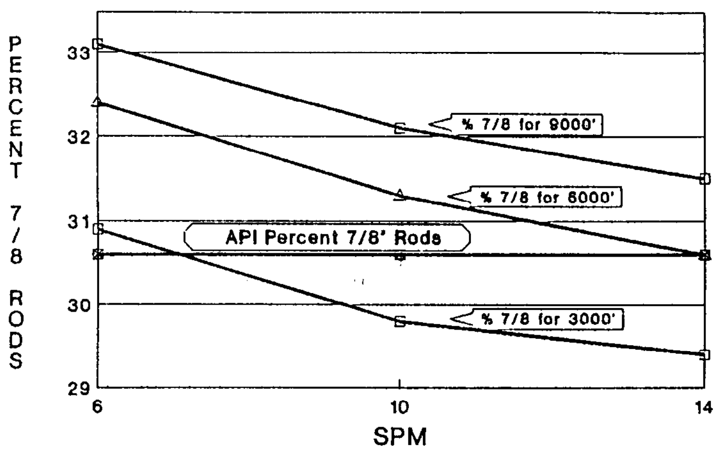
1 Neely, A.B.: "Sucker Rod String Design." Petroleum Engineer March 1976 pp 58-66

2 "Recommended Practice for Design Calculations for Sucker Rod Pumping Systems (Conventional Units)." API RP11L 3rd Ed. (1977)

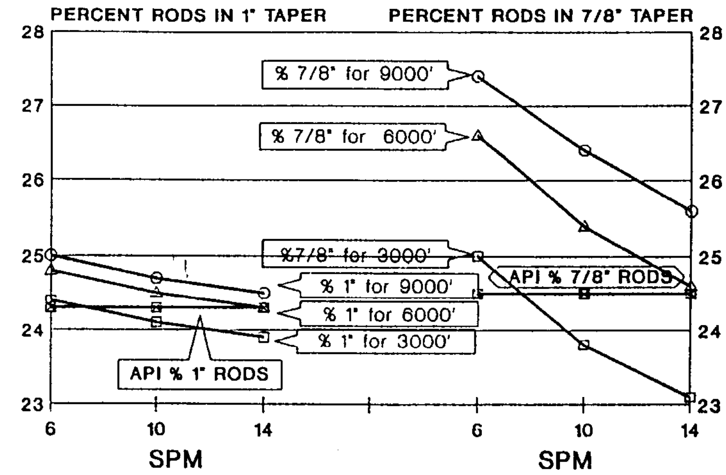
3 Gipson, F. W. and Swaim, H. W.: The Beam Pumping Design Chain. Second Edition, Southwest Petroleum Short Course, Lubbock, Texas, April 1985

4 "Recommended Practice for Care and Handling of Sucker Rods." API RP 11BR 7th Ed. (1986)

COMPARISON - API vs NEELY METHOD TAPER
1.25 Plunger - 76 Grade D Rods



COMPARISON - API vs NEELY METHOD TAPERS
1.25" Pump - 86 Grade D Rods



COMPARISON - API vs NEELY METHOD TAPER
1.5 Plunger - 76 Grade D Rods

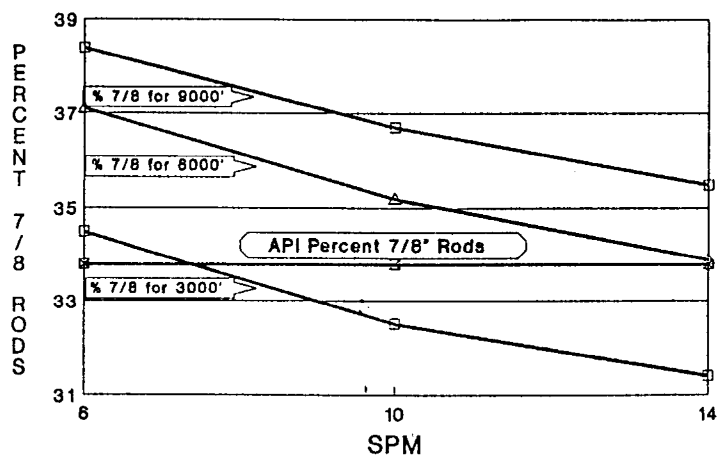


Figure 1

COMPARISON - API vs NEELY METHOD TAPERS
1.5" Pump - 86 Grade D Rods

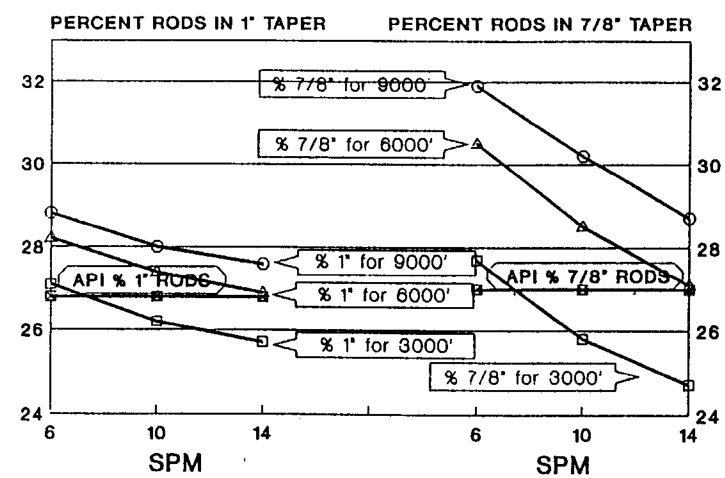
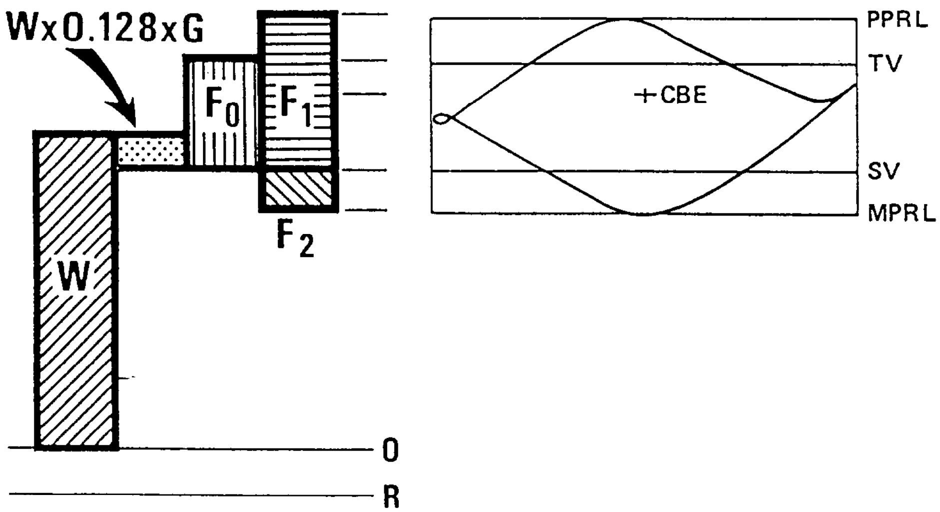


Figure 2

SIX BASIC BEAM PUMPING LOADS



$\boxed{W} = W_r \times L$

$W_{rf} = \boxed{W} - \boxed{W \times 0.128 \times G}$; $W_{rf} = W\,(1.0 - 0.128 \times G)$;

$W_{rf} = SV$

$\boxed{F_0} = 0.340 \times G \times D^2 \times H$; $TV = \boxed{W} - \boxed{W \times 0.128 \times G} + \boxed{F_0}$;

$TV = W_{rf} + F_0$

$\boxed{F_1} = \frac{F_1}{Skr} \times Skr$; $PPRL = \boxed{W} - \boxed{W \times 0.128 \times G} + \boxed{F_1}$;

$PPRL = W_{rf} + F_1$

$\boxed{F_2} = \frac{F_2}{Skr} \times Skr$; $MPRL = \boxed{W} - \boxed{W \times 0.128 \times G} - \boxed{F_2}$;

$MPRL = W_{rf} - F_2$

$CBE = 1.06\,(W_{rf} + 1/2\,F_0)$

Figure 3

WELL CONDITIONS:

$H = 6000$ $S = 120''$ $AREA_{plgr} = 1.767$
$L = 6000'$ $D = 1.5''$ $AREA_{7/8} = 0.601$
$N = 12$ SPM $G = 1$ $AREA_{3/4} = 0.442$

RODS = 76 - API TAPER

SIZE	PCT.	FEET	W_{air}	W_{rf}
7/8"	33.8	2028	4510#	3933#
3/4"	66.2	3972	6490#	5660#
		TOTALS	11000#	9590#

PPRL = 18270#
MPRL = 5966#
Fo = 4590#

TOTAL UPSTROKE DYNAMICS

$PPRL = Wrf + Fo + DYN_{uptotal}$
$DYN_{uptotal} = PPRL - Wrf - Fo = 18270 - 9590 - 4590 = 4090\#$
$DYN_{uprod} = W_{airrod} / W_{airtotal} \times DYN_{uptotal}$
$DYN_{up7/8} = 4510 / 11000 \times 4090 = 1677\#$
$DYN_{up3/4} = 6490 / 11000 \times 4090 = 2413\#$

$PRESSURE_{on\ pump} = 0.433 \times G \times L$
$P_{on\ pump} = 0.433 \times 1 \times 6000 = 2598$ psi

PUMP INTAKE PRESSURE = 0.433 X G X (L - H)
PIP = 0.433 X 1 X (6000-6000) = 0 psi

$PPRL_{3/4} = W_{air3/4} + (P_{on\ pump} \times AREA_{net\ plgr}) + DYN_{3/4} - (PIP \times AREA_{gross\ plgr})$
$= 6490 + (2598 \times (1.767 - 0.442)) + 2413 - (0 \times 1.767)$
$= 12345$ pounds

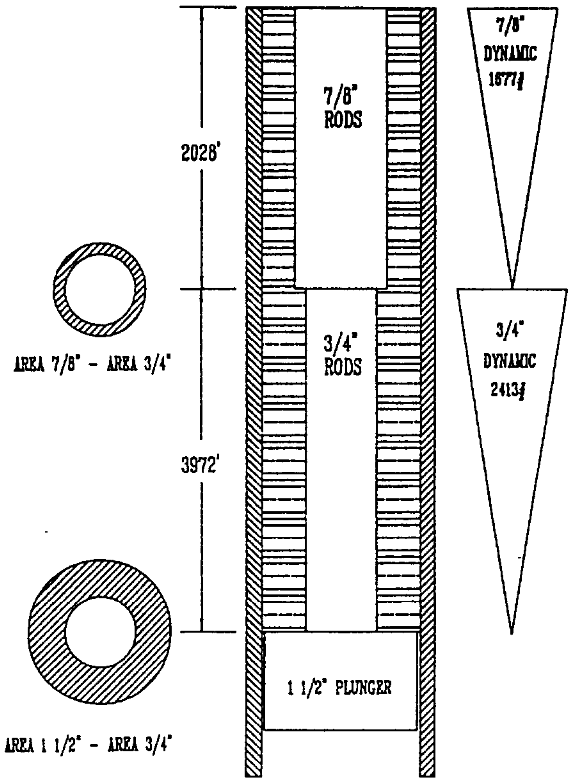
$PEAKSTRESS_{3/4} = 12345 / 0.442 = 27,929$ psi

PRESS. AT BOTTOM 7/8 = 0.433 X 1 X 2028 = 878 psi

$PPRL_{7/8} = PPRL_{3/4} + W_{air7/8} + DYN_{up7/8} - (PRESS_{7/8} \times (A_{7/8} - A_{3/4}))$
$= 12345 + 4510 + 1677 - 878 \times (.601 - .442) = 18392$ pounds

$PEAKSTRESS_{7/8} = 18392 / 0.601 = 30602$ psi

UPSTROKE



UPSTROKE LOADS AND STRESSES

Figure 4

DOWNSTROKE LOADS AND STRESSES

RODS = 76 - API TAPER

SIZE	PCT.	FEET	W_{air}	W_{rf}
7/8"	33.8	2028	4510#	3933#
3/4"	66.2	3972	6490#	5660#
		TOTALS	11000#	9590#

TOTAL DOWNSTROKE DYNAMICS

$MPRL = W_{rf} - DYN_{dntotal}$
$DYN_{dntotal} = W_{rf} - MPRL = 9590 - 5966 = 3624$

$DYN_{dnrod} = W_{airrod} / W_{airtotal} \times DYN_{dntotal}$
$DYN_{7/8} = 4510 / 11{,}000 \times 3624 = 1486$ pounds
$DYN_{3/4} = 6490 / 11{,}000 \times 3624 = 2138$ pounds

PRESSURE AT BOTTOM 3/4" ROD

$P_{bottom\ rod} = 0.433 \times G \times L$
$P_{br} = 0.433 \times 1 \times 6000 = 2598$ psi

$MPRL_{3/4} = W_{air3/4} - P_{br} \times AREA_{3/4} - DYN_{3/4}$
$= 6490 - (2598 \times 0.442) - 2138 = 3204$ pounds

$MINSTRESS_{3/4} = MPRL_{3/4} / AREA_{3/4} = 3204 / 0.442 = 7248$ psi

PRESSURE AT BOTTOM 7/8" ROD

$P_{b7/8} = 0.433 \times G \times L_{7/8} = 0.433 \times 1 \times 2028 = 878$ psi

$MPRL_{7/8} = MPRL_{3/4} + W_{air7/8} - DYN_{7/8} - (P_{b7/8} \times (AREA_{7/8} - AREA_{3/4}))$
$= 3204 + 4510 - 1486 - 878 \times (.601 - .442) = 6088$ lbs

$MINSTRESS_{7/8} = MPRL_{7/8} / AREA_{7/8} = 6088 / 0.601 = 10129$ psi

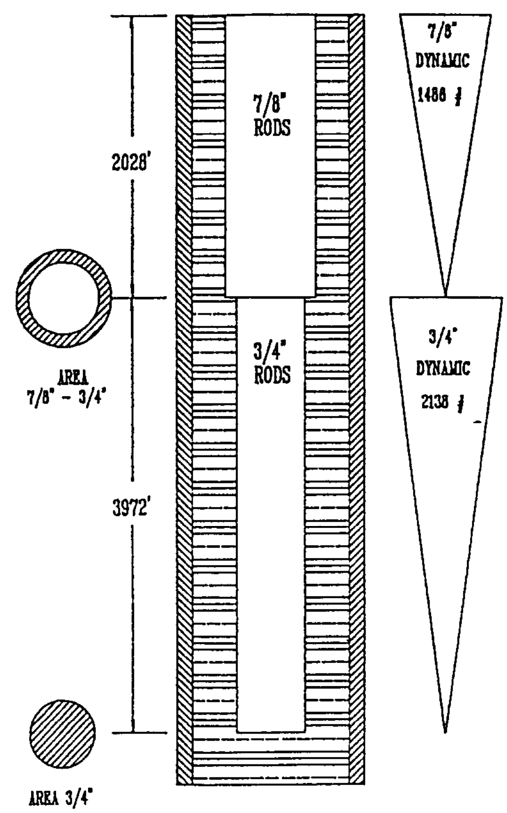
SERVICE FACTOR FOR 3/4" ROD

$SF_{3/4} = PEAKSTRESS_{3/4} / (T/4 + .5625 \times MINSTRESS_{3/4})$
$= 27{,}929 / (28{,}750 + 0.5625 \times 7428) = 0.85$ % LOADED

SERVICE FACTOR FOR 7/8" ROD

$SF_{7/8} = PEAKSTRESS_{7/8} / (T/4 + .5625 \times MINSTRESS_{7/8})$
$= 30602 / (28750 + 0.5625 \times 10129) = 0.89$ % LOADED

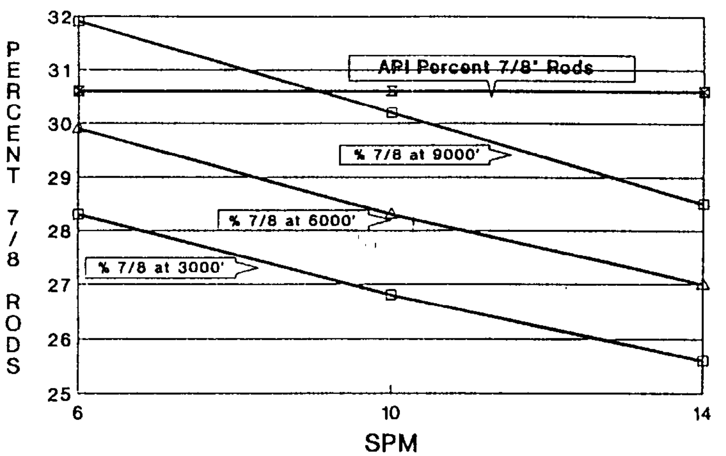
DOWNSTROKE



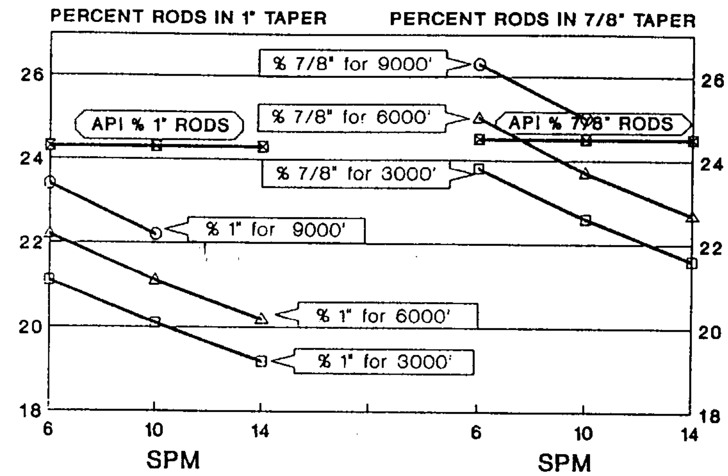
DOWNSTROKE LOADS AND STRESSES

Figure 4A

COMPARISON - API vs EQUAL SF ROD TAPER
1.25 Plunger - 76 Grade D Rods



COMPARISON - API vs EQUAL S.F. TAPERS
1.25" Pump - 86 Grade D Rods



COMPARISON - API vs EQUAL SF ROD TAPER
1.5 Plunger - 76 Grade D Rods

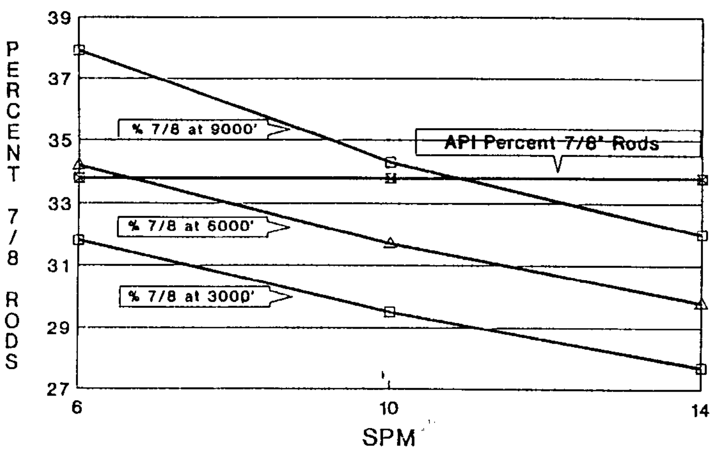


Figure 5

COMPARISON - API vs EQUAL S.F. TAPERS
1.5" Pump - 86 Grade D Rods

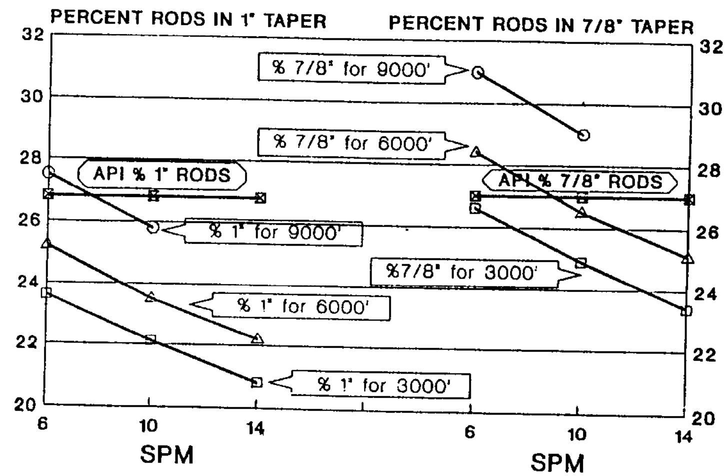


Figure 6

DESIGN CALCULATIONS
for
CONVENTIONAL SUCKER ROD PUMPING SYSTEMS

Refer to API RP 11L for the explanation of this form and the necessary tables and figures required for this calculation.

Company EXAMPLE Well Name ____ Date ____

Field ____ County ____ State ____

Required Pump Displacement, PD ____ bbls./day Maximum Allowable Rod Stress ____ psi

Fluid Level, H = 6000 ft. Pumping Speed, N = 10 SPM Plunger Diameter, D = 1.5 in.

Pump Depth, L = 6000 ft. Length of Stroke, S = 120 in. Spec. Grav. of Fluid, G = 1.0

Tubing Size 2 3/8 in. Is it anchored? Yes No Sucker Rods 76 API, 33.8% 7/8", 66.2% 3/4"

Record Factors from Tables 1 & 2:

1. W_r = 1.833 (Table 4.1, Column 3)
2. E_r = 0.804 10^{-6} (Table 4.1, Column 4)
3. F_c = 1.082 (Table 4.1, Column 5)
4. E_t = – (Table 4.2, Column 5)

Calculate Non-Dimensional Variables:

5. $F_o = .340 \times G \times D^2 \times H = .340 \times$ 1.0 $\times$ 1.5^2 $\times$ 6000 = 4590 lbs.
6. $1/k_r = E_r \times L =$ .804 10^{-6} $\times$ 6000 = 4824 10^{-6} in/lb.
7. $Sk_r = S \div 1/k_r =$ 120 $\div$ 4824 10^{-6} = 24876 lbs.
8. $F_o/Sk_r =$ 4590 $\div$ 24876 = 0.185
9. $N/N_o = NL \div 245{,}000 =$ 10 $\times$ 6000 $\div 245{,}000 =$ 0.245
10. $N/N_o' = N/N_o \div F_c =$ 0.245 $\div$ 1.082 = 0.226
11. $1/k_t = E_t \times L =$ ____ $\times$ ____ = ____ in/lb.

Solve for S_p and PD:

12. S_p/S = 0.92 (Figure 4.1)
13. $S_p = [(S_p/S) \times S] - [F_o \times 1/k_t] =$ [0.92 $\times$ 120] - [____ $\times$ ____] = 110.4 in.
14. $PD = 0.1166 \times S_p \times N \times D^2 = 0.1166 \times$ 110.4 $\times$ 10 $\times$ 1.5^2 = 289 barrels per day

If calculated pump displacement is unsatisfactory make appropriate adjustments in assumed data and repeat steps 1 through 14.

Determine Non-Dimensional Parameters:

15. $W = W_r \times L =$ 1.833 $\times$ 6000 = 10998 lbs.
16. $W_{rf} = W[1 - (.128G)] =$ 10,998 [1-(.128 $\times$ 1)] = 9590 lbs.
17. $W_{rf}/Sk_r =$ 9590 $\div$ 24876 = 0.386

Record Non-Dimensional Factors from Figures 4.2 through 4.6:

18. F_1/Sk_r = 0.35 (Figure 4.2)
19. F_2/Sk_r = 0.15 (Figure 4.3)
20. $2T/S^2k_r$ = 0.28 (Figure 4.4)
21. F_3/Sk_r = 0.22 (Figure 4.5)
22. T_a = 1.02 (Figure 4.6)

Solve for Operating Characteristics:

23. $PPRL = W_{rf} + [(F_1/Sk_r) \times Sk_r] =$ 9590 + [0.35 $\times$ 24876] = 18,270 lbs.
24. $MPRL = W_{rf} - [(F_2/Sk_r) \times Sk_r] =$ 9590 - [0.15 $\times$ 24,876] = 5966 lbs.
25. $PT = (2T/S^2k_r) \times Sk_r \times S/2 \times T_a =$ 0.28 $\times$ 24876 $\times$ 60 $\times$ 10 = 428,945 lb inches
26. $PRHP = (F_3/Sk_r) \times Sk_r \times S \times N \times 2.53 \times 10^{-6} =$ 0.22 $\times$ 24,876 $\times$ 120 $\times$ 10 $\times 2.53 \times 10^{-6} =$ 16.8
27. $CBE = 1.06(W_{rf} + 1/2\,F_o) = 1.06 \times ($ 9590 + 4590/2 $) =$ 12,598 lbs.

Remarks ____

EXHIBIT 1