GAS INTERFERENCE IN ROD PUMPED WELLS

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ABSTRACT

Pumping free gas reduces pump-liquid efficiencies and alters loading on the pumping system. The rod pumping design procedure outlined in API RP 11L assumes complete pump-liquid fillage and determines loads based on test data gathered from an electrical analog computer model. The Shell method is based on a mathematical solution, and the resulting loads are calculated assuming incomplete pump fillage (gas interference). Design charts similar to those used in API RP 11L for rod pumped systems are shown based on 75-percent liquid and 25-percent gas fillage of the pump. These design charts are compared to API rod design charts. In general, incomplete pump fillage alters peak loading conditions; however, loads are not significantly different in most cases from API loads. Surface pump dynamometer cards for 75-percent fillage are compared with 100-percent fillage cards. The shape of the 100- and 75-percent pump fillage dynamometer cards are somewhat different, especially in the first half of the downstroke.

The effects of pumping gas on pump efficiency are shown and explained. The optimum pump volumes and depth plus the important parameters affecting gas separation are outlined.

INTRODUCTION

Gas interference is a common problem in rod-pumped wells. This paper discusses the effect of incomplete pump liquid fillage due to free gas entering the pump. Free gas results in changing the shape of the bottom-hole dynamometer card and in turn the shape of the surface dynamometer card. The changes in shape alter the loads, peak torque, and horsepower and in turn may require a different counterbalance for good operation. Fortunately, the change from complete liquid fillage to only 75-percent fillage causes only minor changes of loads in the normal operating range.

There are a number of methods used as a basis for design of the sucker-rod system. Up until the late 1950's, most designers used semi-empirical formulas which produced only ball-park answers. Often the data that the designs were based on were also inaccurate. Today we need to be a bit more precise in our designs if we wish to remain competitive and minimize capital and operating costs while maximizing production income.

Two design methods were developed in the late 1950's and early 1960's that have proved to be much more reliable than other previously used techniques. One of these is the API method, and the second is the Shell method.

API METHOD

The API method, which is outlined in API RP 11L, is based on results from an electrical analog-computer model. This work was done by Midwest Research Institute for Sucker Rod Pumping Research, Incorporated. A catalog of over 1100 dynamometer cards from the electronic analog computer for many combinations of independent nondimensional parameters was included in the material released to API by Sucker Rod Pumping Research, Incorporated. This design method proved to give good results for most wells where normal conditions were encountered. In general, the cases investigated assumed the following conditions: (1) conventional unit geometry, (2) *full filling of the pump barrel with liquid (no free gas),* (3) small or no prime mover slip, (4) tubing anchored, and (5) negligible fluid acceleration effects. Also, no abnormal friction or mechanical problems were assumed. The design graphs in API RP 11L are average conditions and will result in slight errors for tapered strings and increased damping. For simplified design, only one set of general design graphs were developed rather than graphs for different tapered rod strings and various damping factors.

SHELL METHOD

The Shell method is a mathematical model that involves the solution of a boundary-value problem. The one-dimensional wave equation with viscous damping is used in the sucker-rod boundary-value problem to simulate the behavior of the rod string. This equation describes the longitudinal vibrations in a long slender rod, and its use incorporates into the mathematical model the phenomenon of force wave reflection. The mathematical model described is complicated, and an analytical solution can be obtained only in restricted instances. Solution is obtained by using a partial-difference equation and use of a digital computer. The mathematical model as solved with the partial-difference equation permits accurate prediction of system behavior. The model can be used for both design and surveillance. For design of a sucker rod system, a bottom hole card is assumed and the surface dynamometer card generated (calculated); for surveillance, the surface card is measured and the bottom hole card generated. Both the design and surveillance methods have proved to be reliable, and good results are normally obtained.

Shell has developed design graphs which are similar to the API RP 11L graphs. The same operation conditions as the API were assumed, except Shell developed graphs for 100-, 75-, 50-, and 25-percent liquid fillage. Since about 75-percent pump liquid fillage is a common occurrence, this paper compares the API 100 percent case with the Shell 75-percent case. The 50- and 25-percent cases are rather severe and should be avoided in both the design and operation of the sucker rod system. For simplified the comparison, only the nontapered (uniform) string are considered.

DYNAMOMETER CARD COMPARISON

The *downhole* cards for the API 100-percent liquid fillage and the Shell 75-percent liquid fillage are quite different. (See Figure 1.) The traveling valve opens on the downstroke a quarter of the way down, altering the resulting force wave effects. The magnitude of the force wave will be higher if the pump is filled with low pressure gas. The Shell mathematical model predicts a slightly longer bottom-hole stroke (Sp) than the API analog computer model. Note (Figure 1) that the surface

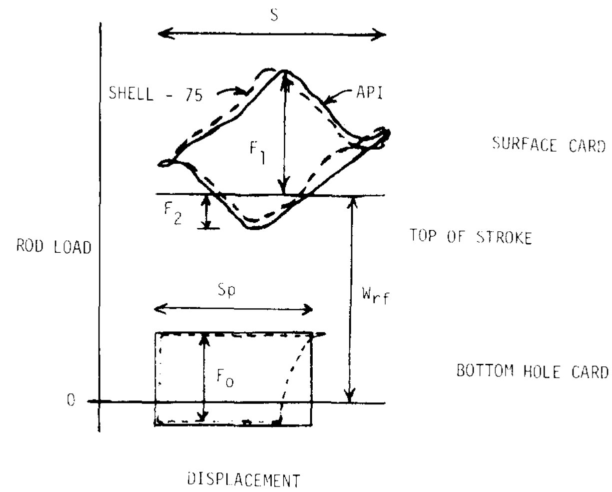

FIGURE 1 - TYPICAL DYNAMOMETER CARD COMPARISON FOR $N/N_o = 0.25$ AND $F_o/SKr = 0.4$

cards are reasonably similar; however, the peak loads (PPRL) often occur at a different displacement location and the Shell 75-percent card does less work in the first half of the downstroke. The Shell method under many conditions will predict smaller F_2 loads than the API method.

Typical (synthetic) dynamometer cards for various independent nondimensional parameters F_o/SKr and N/N_o are given for Shell 75-percent pump liquid fillage. (See Figure 2.) These can be compared with the API 100 percent cards in API Bull 11L2. On field tests, actual surface cards can be taken and compared to the synthetic dynamometer cards. Good comparison should result for cards with the same nondimensional parameter of N/N_o and F_o/SKr. Careful comparison should ascertain if the pump has some free gas fillage.

In comparison of measured cards with calculated cards, the shape rather than the area should be used. The field card can be thin or fat (up and down) depending on the load factor of the dynamometer instrument. The principal diagnostic feature of the surface card lies in the middle two-thirds. A key item is the relative position of the maximum and minimum loads. Remember that the sucker rod system must be in good mechanical condition and have no abnormal friction in order to make such a comparison.

DESIGN

The design graph for the Shell 75-percent liquid fillage are plotted in the same manner as the API

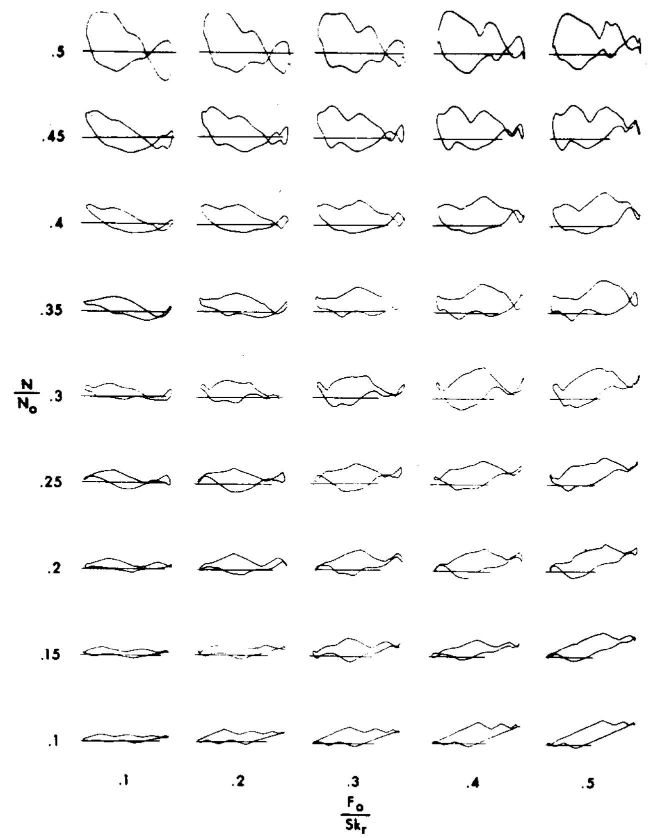

FIGURE 2—SHELL - REPRESENTATIVE DYNAMOMETER CARDS - 75% FILLAGE - UNTAPERED RODS

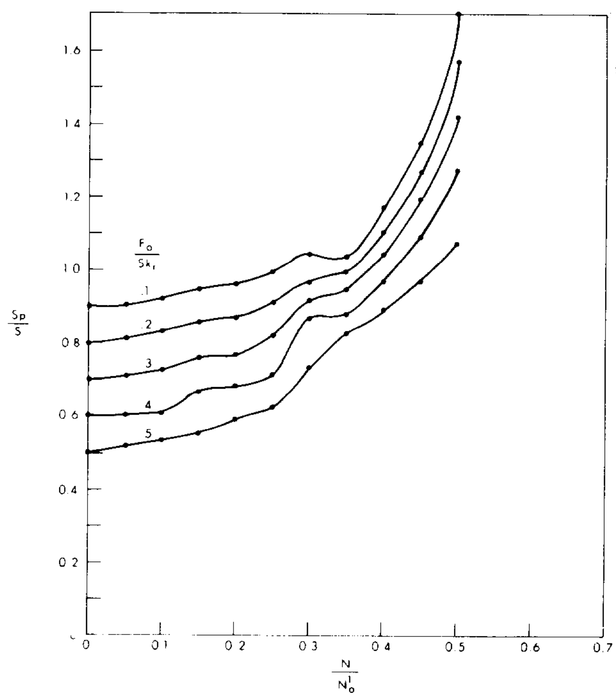

FIGURE 3—PLUNGER STROKE FACTOR SHELL, 75% PUMP LIQUID FILLAGE, UNTAPERED RODS

graphs in RP 11L. (See Figures 3, 4, 5, 6, and 7.) The curves for Shell and API are generally close at nondimension speeds less than 0.2; however, they may vary significantly for F_o/SKr less than 0.4 at N/N_o of 0.5. This seems to imply that the Shell mathematical model assumes a second-harmonic value influence higher than the six percent normally assumed by API. Most operators normally keep pumping speeds relatively low, so that N/N_o is less than 0.4; thus, there are little data to determine which method is more accurate. The minor variations and wiggles are difficult to confirm and make no sizable influence on most designs. In general, the Shell method predicts longer bottom-hole strokes (Figure 3), slightly higher F_1/SKr (Figure 4), slightly lower F_2/SKr values (Figure 5) in the N/N_o range of 0.2 to 0.4.

Peak torque values do not compare well (Figure 6). Shell calculates peak torque by assuming that F_1 and F_2 loads occur in the center of the stroke, that the torque factor is one-half the unit stroke, and that the unit is ideally counterbalanced. Thus,

$$PT = \frac{S}{2}\,\frac{(F_1 + F_2)}{2}$$

The API also assumes ideal counterbalance. Based on experience, units are seldom ideally counterbalanced, and it is a good practice to select a

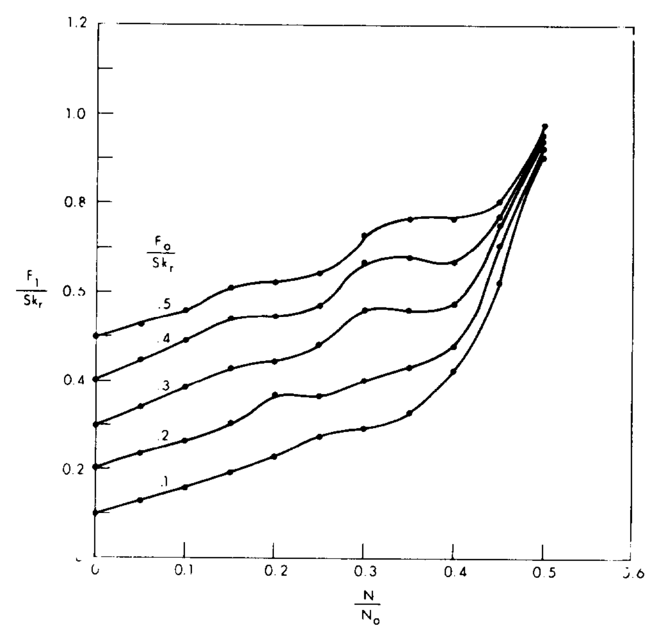

FIGURE 4—PEAK POLISHED ROD LOAD SHELL, 75% PUMP LIQUID FILLAGE, UNTAPERED RODS

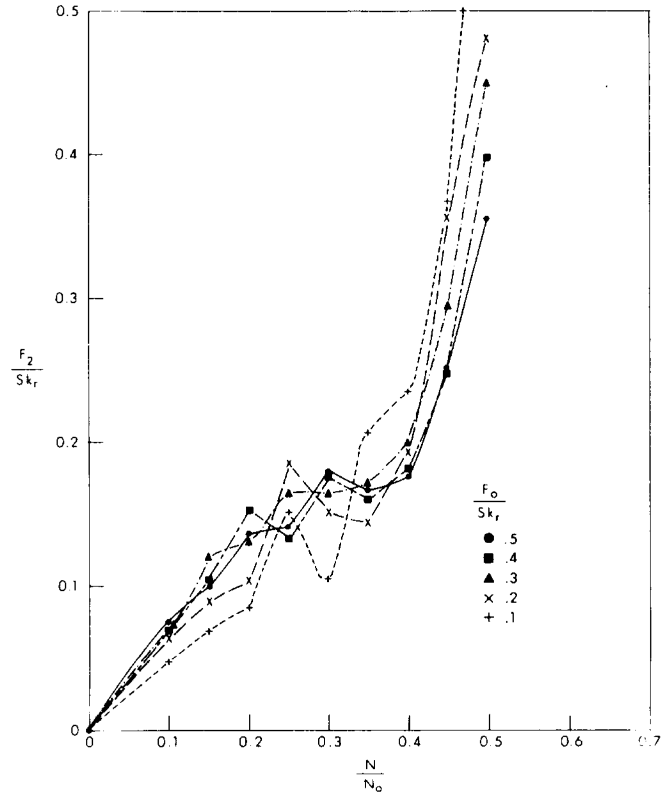

FIGURE 5—MINIMUM POLISHED ROD LOAD SHELL, 75% PUMP LIQUID FILLAGE, UNTAPERED RODS

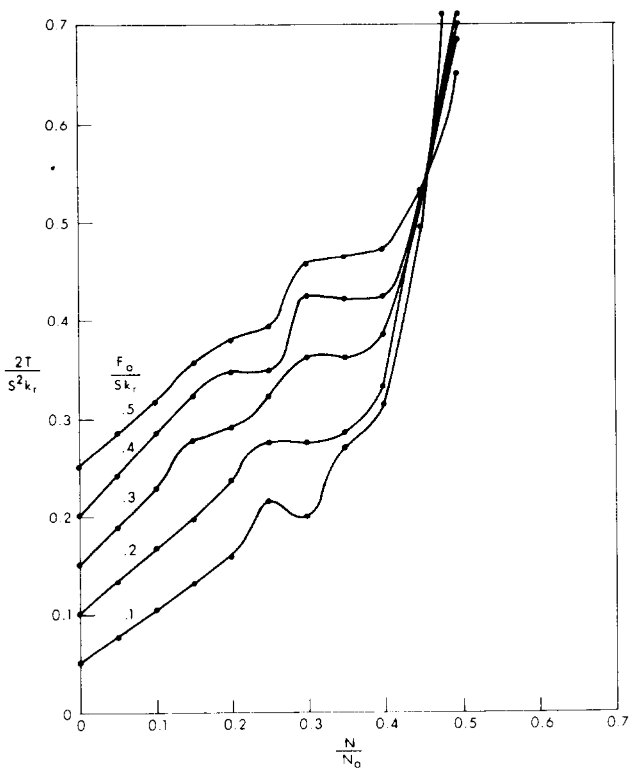

FIGURE 6—PEAK TORQUE SHELL, 75% PUMP LIQUID FILLAGE, UNTAPERED RODS

gear-box peak-torque rating that is at least 10 percent higher than calculated.

The Shell 75-percent pump liquid fillage generally predicts lower polished-rod horsepower than the API method (Figure 7). This is not surprising since less work is done. Note that there is little difference in F_3/SKr for F_o/SKr greater than 0.4. This implies that more fluid can be lifted with larger pumps without substantial increases in polished-rod horsepower. It should be pointed out that the actual prime mover size normally needs to be at least twice the polished-rod horsepower.

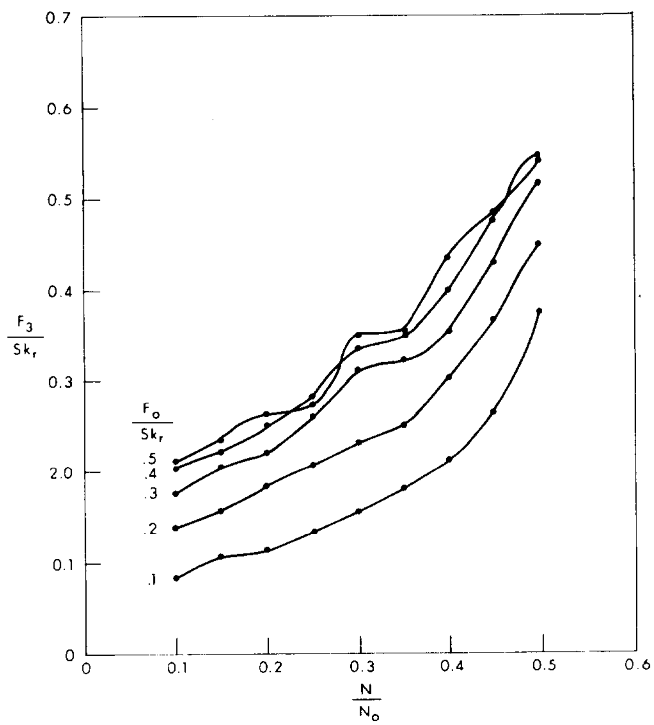

FIGURE 7—POLISHED ROD HORSEPOWER SHELL, 75% PUMP LIQUID FILLAGE, UNTAPERED RODS

DESIGN CALCULATION COMPARISON

A design for a typical well using both the API and Shell methods are shown in Figures 8 and 9. The Shell 75-percent case has a 13-percent longer bottom-hole stroke, a 15-percent higher minimum load, a 10-percent less peak torque, and a 13-percent lower polished-rod horsepower than the API 100-percent case. Possibly, you could squeeze by using the Shell method with a C-114-133-54 unit if future loading conditions are expected to decline rather than increase.

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

Company **API** Well Name **100 %** Date **4-79**
Field **SWPSC** County ___ State **TX**
Required Pump Displacement, PD ___ bbls./day — Maximum Allowable Rod Stress **30,000** psi
Fluid Level, H = **4500** ft. — Pumping Speed, N = **16** SPM — Plunger Diameter, D = **1.5** in.
Pump Depth, L = **5000** ft. — Length of Stroke, S = **54** in. — Spec. Grav. of Fluid, G = **.9**
Tubing Size **2** in. Is it anchored? Yes No — Sucker Rods **ALL 3/4"**

Record Factors from Tables 1 & 2:

1. W_r = **1.634** (Table 1, Column 3)
2. E_r = **.883 x 10^-6** (Table 1, Column 4)
3. F_c = **1.0** (Table 1, Column 5)
4. E_t = **—** (Table 2, Column 5)

Calculate Non-Dimensional Variables:

5. $F_o = .340 \times G \times D^2 \times H = .340 \times$ ___ x ___ x ___ = **3098** lbs.
6. $1/k_r = E_r \times L$ = ___ x ___ = **.00441** in/lb.
7. $Sk_r = S \div 1/k_r$ = ___ ÷ ___ = **12,232** lbs.
8. F_o/Sk_r = ___ ÷ ___ = **.253**
9. $N/N_o = NL \div 245{,}000$ = ___ x ___ ÷ 245,000 = **.327**
10. $N/N_o' = N/N_o \div F_c$ = ___ ÷ ___ = **.327**
11. $1/k_t = E_t \times L$ = ___ x ___ = **—** in/lb.

Solve for S_p and PD:

12. S_p/S = **.86** (Figure **4.1**)
13. $S_p = [(S_p/S) \times S] - [F_o \times 1/k_t]$ = [___ x ___] - [___ x ___] = **46** in.
14. $PD = 0.1166 \times S_p \times N \times D^2 = 0.1166 \times$ ___ x ___ x ___ = **195** 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. $W = W_r \times L$ = ___ x ___ = **8170** lbs.
16. $W_{rf} = W[1 - (.128G)]$ = ___ [1-(.128 x ___)] = **7229** lbs.
17. W_{rf}/Sk_r = ___ ÷ ___ = **.591**

Record Non-Dimensional Factors from Figures 3 through 7:

18. F_1/Sk_r = **.48** (Figure **4.2**)
19. F_2/Sk_r = **.215** (Figure **4.3**)
20. $2T/S^2k_r$ = **.375** (Figure **4.4**)
21. F_3/Sk_r = **.3** (Figure **4.5**)
22. T_a = **.95** (Figure 7)

Solve for Operating Characteristics:

23. $PPRL = W_{rf} + [(F_1/Sk_r) \times Sk_r]$ = ___ + [___ x ___] = **13100** lbs.
24. $MPRL = W_{rf} - [(F_2/Sk_r) \times Sk_r]$ = ___ - [___ x ___] = **4599** lbs.
25. $PT = (2T/S^2k_r) \times Sk_r \times S/2 \times T_a$ = ___ x ___ x ___ x ___ = **118,000** lb inches
26. $PRHP = (F_3/Sk_r) \times Sk_r \times S \times N \times 2.53 \times 10^{-6}$ = ___ x ___ x ___ x ___ x 2.53×10^{-6} = **8**
27. $CBE = 1.06(W_{rf} + 1/2\ F_o) = 1.06 \times$ (___ + ___) = **9305** lbs.

Remarks ___

API Form No. 11L-1

FIGURE 8 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 **SHELL** Well Name **75%** Date **4-79**
Field **SWPSC** County ___ State **TX**
Required Pump Displacement, PD **150** bbls./day — Maximum Allowable Rod Stress **30,000** psi
Fluid Level, H = **4500** ft. — Pumping Speed, N = **16** SPM — Plunger Diameter, D = **1.5** in.
Pump Depth, L = **5000** ft. — Length of Stroke, S = **54** in. — Spec. Grav. of Fluid, G = **.9**
Tubing Size **2** in. Is it anchored? Yes No — Sucker Rods **ALL 3/4"**

Record Factors from Tables 1 & 2:

1. W_r = **1.634** (Table 1, Column 3)
2. E_r = **.883 x 10^-6** (Table 1, Column 4)
3. F_c = **1.0** (Table 1, Column 5)
4. E_t = **—** (Table 2, Column 5)

Calculate Non-Dimensional Variables:

5. $F_o = .340 \times G \times D^2 \times H = .340 \times$ ___ x ___ x ___ = **3098** lbs.
6. $1/k_r = E_r \times L$ = ___ x ___ = **.00441** in/lb.
7. $Sk_r = S \div 1/k_r$ = ___ ÷ ___ = **12,232** lbs.
8. F_o/Sk_r = ___ ÷ ___ = **.253**
9. $N/N_o = NL \div 245{,}000$ = ___ x ___ ÷ 245,000 = **.327**
10. $N/N_o' = N/N_o \div F_c$ = ___ ÷ ___ = **.327**
11. $1/k_t = E_t \times L$ = ___ x ___ = **—** in/lb.

Solve for S_p and PD:

12. S_p/S = **.96** (Figure **4.1B**)
13. $S_p = [(S_p/S) \times S] - [F_o \times 1/k_t]$ = [___ x ___] - [___ x ___] = **52** in.
14. $PD = 0.1166 \times S_p \times N \times D^2 = 0.1166 \times$ ___ x ___ x ___ = **218** barrels per day **x .75 = 163.5 OK**

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

Determine Non-Dimensional Parameters:

15. $W = W_r \times L$ = ___ x ___ = **8170** lbs.
16. $W_{rf} = W[1 - (.128G)]$ = ___ [1-(.128 x ___)] = **7229** lbs.
17. W_{rf}/Sk_r = ___ ÷ ___ = **.591**

Record Non-Dimensional Factors from Figures 3 through 7:

18. F_1/Sk_r = **.48** (Figure **4.2B**)
19. F_2/Sk_r = **.16** (Figure **4.3B**)
20. $2T/S^2k_r$ = **.32** (Figure **4.4B**)
21. F_3/Sk_r = **.275** (Figure **4.5B**)
22. T_a = **—** (Figure 7)

Solve for Operating Characteristics:

23. $PPRL = W_{rf} + [(F_1/Sk_r) \times Sk_r]$ = ___ + [___ x ___] = **13100** lbs. **/.442 = 29,638 psi OK**
24. $MPRL = W_{rf} - [(F_2/Sk_r) \times Sk_r]$ = ___ - [___ x ___] = **5272** lbs.
25. $PT = (2T/S^2k_r) \times Sk_r \times S/2 \times T_a$ = ___ x ___ x ___ x ___ = **106,044** lb inches
26. $PRHP = (F_3/Sk_r) \times Sk_r \times S \times N \times 2.53 \times 10^{-6}$ = ___ x ___ x ___ x ___ x 2.53×10^{-6} = **7**
27. $CBE = 1.06(W_{rf} + 1/2\ F_o) = 1.06 \times$ (___ + ___) = **9305** lbs.

Remarks ___

API Form No. 11L-1

FIGURE 9—DESIGN CALCULATIONS FOR CONVENTIONAL SUCKER ROD PUMPING SYSTEMS

TYPICAL PUMPING CASE

Pumping free gas in an oil well is a common problem that cannot easily be avoided. It is highly desirable to let the free gas vent up the casing annulus rather than have it reduce pump efficiency. A typical pumping case is shown in Figure 10. Shown is a plot of the flowing bottom-hole pressure (P_{wf}) versus the production rate. The *IPR* curve is shown in conjunction with the total liquid and gas volume curve. In this case, we have installed a sucker-rod system with a pump displacement 12.5 percent higher than the maximum possible oil and water production. The pump performance curve is also drawn which shows the volume of liquid in the pump and the volume of free gas at various pressures. The intersection of the pump performance curve and the IPR curve is the operating condition. Thus, the free gas in the pump will be slightly over 25 percent and the liquid fillage less than 75 percent.

There are several approaches to increase production in a well of this type. Installation of a more effective gas anchor would vent more gas, thus shifting the pump-performance curve to the right so that the intersection with the IPR curve would be at an increased production rate. Increasing the pump displacement would also move the pump-performance curve to the right and increase production. Also, theoretically, the pump could be moved up hole, which would move the IPR down

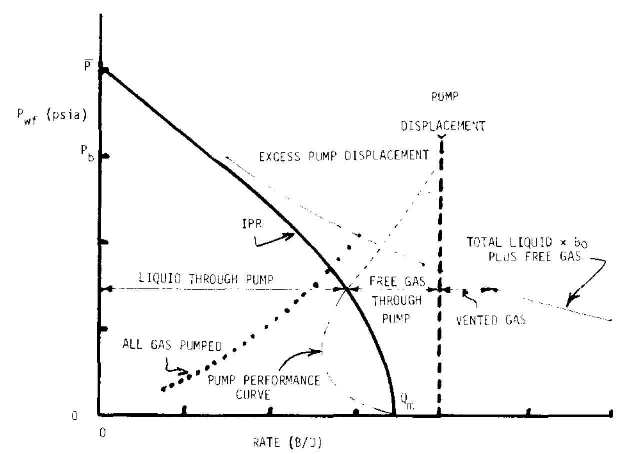

FIGURE 10—TYPICAL PUMPING CASE

and alter the pump performance curve — increasing production slightly. Of these choices, the use of a more effective gas anchor is the best solution. The natural or packer gas anchor should be considered in such cases. Even under the best design condition, wells such as this must still pump some free gas. Thus care should be taken in the selection of the pump and the spacing of the pump in the well.

CONCLUSIONS

1. The change from complete liquid fillage (API) to only 75 percent liquid fillage (Shell) causes minor changes of loads.
2. The Shell method predicts lower F_2 values and consequently lower peak-torque values and polished-rod horsepower than the API method for most operating conditions.
3. The Shell method indicates a higher second-harmonic value than the API method and predicts a longer bottom-hole stroke — especially for a low F_o/SKr value.
4. The Shell-calculated surface dynamometer cards are different (less work) from the API cards, primarily in the first half of the downstroke area.
5. The design calculations are reasonably close for the API and Shell methods.
6. Typical pumping installation for oil wells must handle free gas and should be equipped with an effective gas anchor.

NOMENCLATURE

CBE — Counterweight required, pounds
D — Plunger diameter, inches
E — Modulus of elasticity, psi
F_c — Frequency factor
F_o — Differential fluid load on full plunger area, pounds
F_1 — PPRL factor
F_2 — MPRL factor
F_3 — PRHP factor
G — Specific gravity of produced fluid
H — Net lift, feet
1/Kr — Elastic constant of total rod string, inches per pound
1/Kt — Elastic constant of tubing string, inches per pound
L — Pump depth, feet
MPRL — Minimum polished-rod load, pounds
N — Pumping speed, strokes per minute, spm
N_o — Natural frequency of untapered-rod string, spm
N_o' — Natural frequency of tapered-rod string, spm
$\bar{P}$ — Static bottom-hole reservoir pressure, psia
Pb — Bubble point, psia
PD — Pump displacement, barrels per day
PPRL — Peak polished-rod load, pounds
PRHP — Polished-rod horsepower, HP
PT — Peak crank torque, inch pounds
P_{wf} — Producing bottom hole pressure, psia
S — Surface polished-rod stroke, inches
SKr — Pounds of load necessary to stretch the total rod string an amount equal to the polished-rod stroke
Sp — Bottom-hole pump stroke, inches
W — Total weight of rods in air, pounds
Wr — Average unit weight of rods in air
W_{rf} — Total weight of rods in fluid, pounds

F_o/SKr — Nondimensional load
F_1/SKr — Nondimensional PPRL
F_2/SKr — Nondimensional MPRL
F_3/SKr — Nondimensional PRHP
N/N_o — Nondimensional speed
Sp/S — Nondimensional stroke
$2T/S^2Kr$ — Nondimensional PT

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