# FUNDAMENTALS OF WELL ANALYSIS

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A well analysis program is an area where any oil company can make money immediately. It appears that most well analyses are performed by large oil companies that have large computer facilities. However, in order to use these facilities, a great deal of effort is required on the part of the engineer or technician. Quite often, the engineer could make a few calculations with a small calculator and have the answer to the problem. This requires that the engineer understand the basic principles of the pump, rod string, and pumping unit operation.

Equipment to obtain the necessary data was hard to use and required considerable time. Usually, the pumping system had severe problems before the time and effort would be spent to analyze it. Now, equipment is available that will allow the engineer or technician to obtain the data easily and make an analysis in a few minutes.

Of primary importance is a thorough understanding of the operation of a modern oil well pump. Figure 1 is a schematic drawing of such a pump.

There are three main components of an oil well pump: (1) the standing valve (SV), (2) the traveling valve (TV), and (3) the pump barrel. The SV is located in the bottom of the pump barrel and opens or closes, depending on the relationship between the pressure P1 and P3. The TV is located in the plunger and opens or closes, depending on the relationship of the pressures P2 and P3.

The operation of the pump is as follows. Assume that the pump plunger is at its lowest point and is starting to move upward. As the pump plunger stops and begins to move upward, the TV closes because pressure P2 is the same as pressure P3, and the weight of the TV causes it to fall into its seat. With the TV closed and moving upward, pressure P3 is reduced. When the pressure difference between P1 and P3 is great enough, the SV will be forced open. This allows well fluid to flow into the pump barrel. As the plunger rises, the pump barrel continues to fill. Note that the reason for the pump barrel filling was the plunger moving upward which reduced pressure P3. When the plunger stops its upward movement at its topmost position, pressures P1 and P3 equalize and the SV closes because of its own weight. When the plunger starts down, it will be forced into the fluid in the pump barrel which will cause pressure P3 to increase above pressure P2, thus opening the TV. This allows the plunger to travel to its lowermost position, and the cycle is repeated. The above description is based upon fluid being available to fill the pump barrel.

The next element in the pumping system is the rod

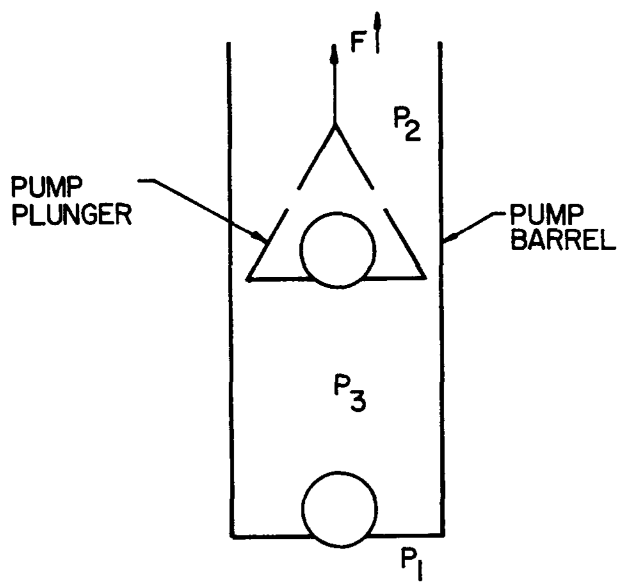


FIG. 1 SCHEMATIC OF OIL WELL PUMP

string. The function of the rod string is to connect the pump plunger to the pumping unit. The rod string can be made up of only one size rod or several sizes. A rod string made up of more than one size rod is called a tapered string; the rod sizes are in descending order with the largest rods on top. Dynamically, the rod string can be considered as a very long spring which connects the driving force (pumping unit) to the load (pump plunger). The dynamic effect will be discussed later.

The remaining element in the pumping system is the pumping unit which is driven by an engine or electric motor. The pumping unit converts the rotary motion of an engine or electric motor into reciprocating motion by means of gears and linkage systems. Since the load on the pumping unit is different on the up and down strokes, a means of counterbalancing is necessary. For most units, weights are used as counterbalancing for the changing loads. Counterbalancing a pumping unit reduces the peak torque on the gearbox and reduces the size of the prime mover required to run the pumping system.

When the above three elements (pump, rod string and pumping unit) are combined into a single system, various measurements and calculations can be made which show how well the entire system is performing. The American Petroleum Institute (API) has set standards for various constants and methods for making these calculations. Therefore, the API standards for calculations and definitions will be used where applicable. A bibliographical listing is included in this paper.

The definitions used in this paper are as follows:

- $L$ = length of rod string (ft)
- $H$ = distance from surface to fluid in casing (ft)
- $S$ = stroke length (in.)
- $N$ = pumping speed (SPM)
- $N_o$ = natural frequency of nontapered rod string (SPM)
- $N_o'$ = natural frequency of tapered rod string (SPM)
- $D$ = pump plunger diameter (in.)
- $G$ = specific gravity of fluid in the tubing
- $W_r$ = weight of rods per foot in air (lb/ft) (obtained from API RP11L, Table 1)
- $W$ = total weight of rods in air (lb)
- $W_{rf}$ = total weight of rods immersed in well fluid (lb)
- $E_r$ = elastic constant of rod string (in./lb-ft) (obtained from API RP11L, Table 1)
- $F_c$ = frequency factor for tapered rod strings (obtained from API RP11L, Table 1)
- SV = standing valve
- TV = traveling valve
- $SK_r$ = static load required to stretch the rod string an amount equal to the stroke length (lb)
- $F_o$ = static fluid load on the pump plunger (lb)
- $F_1$ = static fluid load on the pump plunger plus the dynamic effects on the upstroke (lb)
- $F_2$ = dynamic effects on the downstroke (lb)
- PPRL = peak polished rod load during a pumping cycle (lb)
- MPRL = minimum polished rod load during a pumping cycle (lb)
- CBE = counterbalance effect

Well Analysis is simply asking a series of questions whose answers will show whether the pumping system is performing as desired and/or designed. Some of these questions are as follows:

1. Does the current production of this well match the pumping capacity of this pumping system?
2. What is the fluid level in the casing?
3. Is the shape of the dynagraph as it should be?
4. Is the SV load located at the proper point on the dynagraph?
5. Does the SV load change over a short period of time (5-10 sec)?
6. Is the separation of the SV load and TV load correct?
7. Does the TV load change over a short period of time (5-10 sec)?
8. Are the PPRL and MPRL reasonable for this well?
9. What is the rod stress range?
10. Is the pumping unit counterbalanced correctly?
11. What is the peak gearbox torque?

In the past, it has been difficult to obtain answers to some of the above questions. It requires considerable effort even if an electronic calculator is used. If these calculations are done by hand, they are so time-consuming that very few people will do them. Also, obtaining the data to make the calculations was a task generally requiring two men for an hour or more. However, equipment is now available that will allow one man to obtain the data and make the necessary calculations within 15 to 20 minutes.

The dynagraph is the primary element in analyzing the performance of a pumping system. Much has been written about dynagraphs and their use. This paper will deal only with the fundamentals of the dynagraph and the elements composing it.

An important aspect of well analysis is the shape of the dynagraph. The shape of the dynagraph is the result of several interacting forces, both static and dynamic. If the rod string were completely inelastic and no inertia existed, the dynagraph would be a rectangle as shown in Fig. 2.

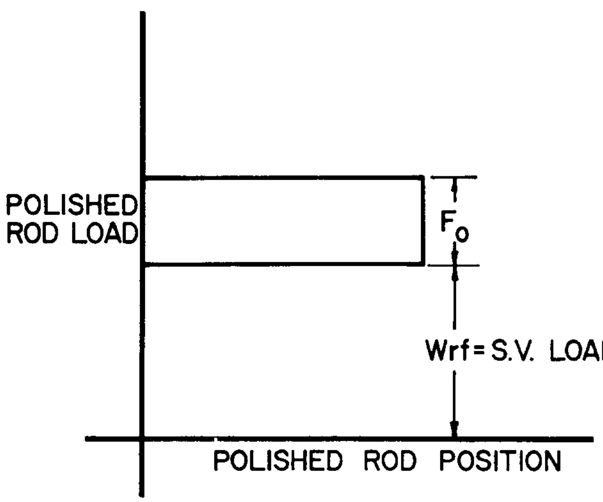


FIG. 2 IDEAL DYNAGRAPH

However, the rod string is very elastic and there is a considerable amount of inertia in the pumping system. Therefore, a rectangular shaped dynagraph is approached only as the pumping speed or rod string length approaches zero. Figure 3 shows a stylized dynagraph and its various components.

The SV load is the total weight of the rods in air minus the bouyancy of the rods in the fluid. The API defines this parameter as $W_{rf}$. The TV load is the SV load plus the static fluid load on the pump plunger

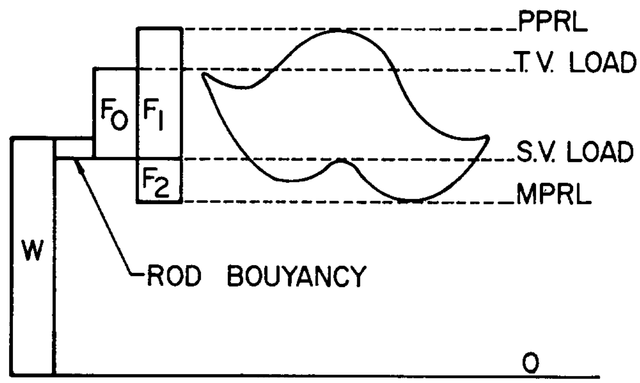


FIG. 3 STYLIZED DYNAGRAPH AND ITS COMPONENTS

($F_o$). Therefore, the separation of the TV and SV loads is always the static fluid load ($F_o$). The PPRL is the SV load plus $F_1$. $F_1$ is $F_o$ plus the dynamic effects on the upstroke. The MPRL is the SV load minus $F_2$; $F_2$ is the dynamic effects on the downstroke.

All of the above components (MPRL, SV load, TV load and PPRL) can be calculated for a given pumping system. The various constants and graphs required to perform these calculations can be found in API RP11L. An example of the API standard design calculations for a conventional sucker rod pumping system is shown in the Appendix.

At this point, answers to the questions can be obtained. All further discussions will assume that the pump is filling properly on each pump stroke.

The answer to the first question is generally the first indication that a problem exists. That is: "Does the current production of this well match the pumping capacity of this pumping system?" Most problems are first noticed as a result of a production test. The production test can be once per month or oftener. But the main point is that it is not known when the well began to have a problem. Obviously, the shorter the intervals between well tests, the better. However, if a regular program of well monitoring and analysis is in effect, the problems can sometimes be prevented entirely or at least detected sooner.

The pumping system capacity in barrels per day can be determined from the following formula:

Pumping Capacity = $(0.1166)(S_P)(N)(D^2)$

$S_p$ is the pump stroke length and is obtained from Fig. 4.1, API RP11L. Efficiency factors are usually used with the above formula to account for gas and water. The next question is "What is the fluid level

(H) in the casing?" The fluid level is obtained by means of an acoustical fluid level detector.

The next question is, "Is the shape of the dynagraph as it should be?" In order to make this determination, three parameters are required: (1) $F_o/SK_r$; (2) $N/N'_o$; and (3) the slip of the prime mover.

$F_o = (0.34)(G)(D^2)(H)$

$SK_r = (S)/(E_r)(L)$

$N/N'_o = (N)(L)/(245{,}000)(F_c)$

$E_r$ and $F_c$ are found in Table I of API RP11L for the applicable rod string.

The slip of the prime mover means "How much does the speed of the prime mover change during a pumping cycle?" If the prime mover is an electric motor that is fully loaded at the peak torque points, determining the slip is easy. The slip in this case would be the synchronous motor speed, generally 1200 or 1800 rpm, minus the full load speed (obtained from nameplate). This result is divided by the synchronous speed and multiplied by 100 to give the slip in percent.

Refer to the section on Analog Computer Dynamometer Cards, in API Bul 11 L2 and locate the page with the $F_o/SK_r$ and $N/N'_o$ nearest to the values calculated above. Then locate on the page the dynagraph with the appropriate rod string taper and prime mover slip.

Using a dynamometer, record the dynagraph of the pumping system. Also show the SV load, TV load and CBE on the dynagraph. If the pumping system under analysis is functioning properly, the recorded dynagraph should be similar to the one located in API BUL 11 L2. If it is not similar, the analyst must determine why. Some of the reasons why the two dynagraphs would be different are:

1. The well is pumped-off.
2. The pump is gas-locked.
3. The pump has excessive friction.
4. Wrong data were used in calculations.
5. The well is flowing.

The next question is, "Is the SV load located at the proper point on the dynagraph?" When measuring the SV and TV loads, care must be taken to get a good measurement. These are very important measurements. The brake must be applied smoothly so that the rod string does not stop abruptly. The SV load measurement must be made with the TV open and the SV closed. This can be accomplished by stopping the pumping unit smoothly on the downstroke below any indication of fluid pound or gas lock. This measurement should be made several times. Take the lowest value and be sure that the measurement repeats. Similarly, the TV measurement must be made with the SV open and the TV closed. In this case, take the highest value.

Refer to API BUL 11L2. The line drawn horizontally near the bottom of each dynagraph is where the SV load line should be on the recorded dynagraph. As previously stated, the SV load is the weight of the rod string in the well fluid and can be calculated by the following formula:

$$\text{SV load} = W_{rf} = (W_r)(L)(1 - 0.128G)$$

$W_r$ is obtained from Table 1 of API RP11L. The term (1-0.128G) accounts for the bouyancy of the rod string in the well fluid.

If the SV load measurement changes over a short period of time, a leak is indicated.

The next question is: "Is the separation of the SV load and the TV load correct?" The separation of the SV load and TV load is the fluid load on the pump plunger ($F_o$). Compare the actual separation with the calculated value of $F_o$. If the calculated and measured values for $F_o$ do not agree, the analyst must determine the reason for the difference. Some reasons are: wrong value for G, fluid level in error, hole in tubing, etc. If the calculated $F_o$ is incorrect, the dynagraph shape obtained from API BUL 11L2 probably does not compare well with the recorded dynagraph.

If the TV load changes over a short period of time, a leak is indicated.

The next question is: "Are the PPRL and MPRL reasonable for this well?" These loads can be calculated by using the following formulas:

$$PPRL = W_{rf} + (F_1/SK_r)(SK_r)$$

$$MPRL = W_{rf} - (F_2/SK_r)(SK_r)$$

$F_1/SK_r$ is obtained from the graph shown in Fig. 4.2 of API RP11L. $F_2/SK_r$ is obtained from the graph shown in Fig. 4.3 of API RP11L. Both quantities are functions of $F_o/SK_r$ and $N/N'_o$, which were calculated earlier.

A reasonable correlation between the actual measured values and calculated values is 10%. If the values differ by more than 10% an attempt should be made to determine why. However, it should be pointed out, a difference of greater than 10% does not mean a problem exists.

The next question is: "What is the rod stress range?" This is a very important question since rod parts are a major reason for using pulling units. The allowable stress range for a specified type of rod string is defined by the API modified Goodman stress diagram. Basically, this diagram says that as the peak rod stress increases, the minimum rod stress must also increase. An API modified Goodman diagram is shown in Fig. 4 for grade C rods. The actual stress range is calculated as follows:

Stress (max) = (PPRL) / (area of rod)

Stress (min) = (MPRL) / (area of rod)

Stress range = Stress (max) - Stress (min)

The stress range allowed by the API modified Goodman diagram is calculated as follows:

Stress (max) = 22500 + 0.5625 (stress (min) )

Allowable Stress range = Stress (max allow) - Stress (min)

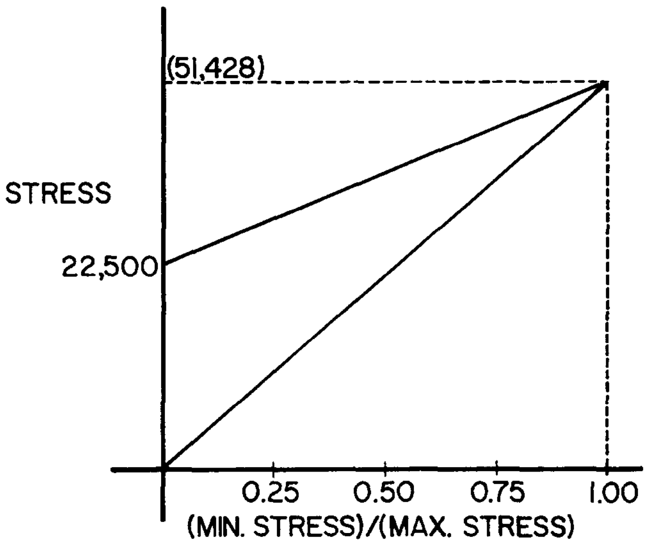


FIG. 4 API MODIFIED GOODMAN DIAGRAM FOR GRADE C RODS

Another factor that must be considered in the allowable rod stress range is the corrosive character of the well fluid. If salt water or $H_2S$ are present, the allowable stress range must be reduced by the appropriate service factor. For salt water, the service factor is approximately 0.90. For $H_2S$, it is approximately 0.60. Refer to API SPEC 11B, Specifications for Sucker Rods, for a more detailed discussion of the use of the API modified Goodman diagram.

The last two questions are: "Is the pumping unit counterbalanced correctly?", and "What is the gearbox torque?" These questions are both related and independent, in that a pumping unit can be counterbalanced correctly and the peak gearbox torque can exceed the rating of the gearbox. Therefore, both questions must be answered. Both questions can be answered by the same set of calculations by calculating the gearbox torque according to the API recommended practice. However, this is a very laborious task because the gearbox torque must be calculated every 15° of crank rotation. A much faster way to determine if the unit is counterbalanced correctly is to plot the pumping unit motor current versus polished rod position. If the pumping unit is properly counterbalanced, the peaks of the current on the up and down strokes will be the same. Figure 5 shows a typical motor current versus polished rod position plot. Note the current on the upstroke is much the same as the current on the downstroke. This plot can be made at the same time the dynagraph is made. A quick inspection is all that is necessary to show the relative counterbalance of the pumping unit.

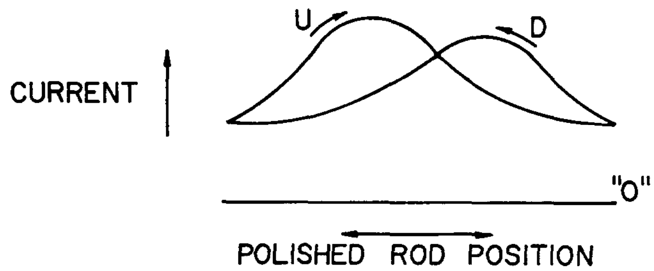


FIG. 5 – PUMPING UNIT POWER GRAPH

Next is the calculation of the peak torque on the gearbox. This is the most time-consuming and difficult task of the entire analysis. Fortunately, it does not have to be done every time the well is checked. It is only necessary to make these calculations once for a given pumping system installation unless the installation has a gearbox torque very near the gearbox rating. In this case, a change in gearbox torque will be reflected as a change in the current plot. Therefore, if the current plot changes, it might be desirable to calculate the gearbox torque again.

The net torque on the gearbox is made up of two components:

1. Polished rod load reflected through the walking beam, pitmans and crank to the

gearbox.

2. Counterbalance weights whose effect is a function of their position on the crank and varies as a sine function of the crank angle.

The torque, as a result of the polished rod load, is the polished rod load at the specified crank angle times the torque factor at the specified crank angle, $\theta$.

It is defined by the formula:

$$T_{PRL} = (PRL - SU)\ (TF)$$

The torque as a result of the counterbalance weights is defined by the formula:

$$T_{CBE} = (CBE - SU)\ (TF_{CBE\phi})\ (\sin\theta)$$

SU is the structural unbalance of the pumping unit and is obtained from the manufacturer of the pumping unit. $TF_{CBE\phi}$ is the torque factor of the pumping unit at the angle at which the CBE was measured.

The net torque on the gearbox is given by the formula:

$$T_N = T_{PRL} - T_{CBE}$$

The torque factors and rod position as functions of the crank angle must be either obtained from the manufacturers of the pumping unit or calculated. These parameters are very difficult to calculate by hand and are best done by a computer. Programs for small hand-held programmable calculators are available to make all of the above calculations.

The API standard method for calculating torque requires that the torque be calculated every 15° of crank angle. If only the peak torque is desired, it can generally be found with four or five points after a little experience.

Figure 6 shows a typical dynagraph and current plot for a pumping system. Note the shape of the dynagraph, location of the SV and TV loads, location of the CBE line and current plot. The current plot shows the pumping unit to be counterbalanced very well. This is supported by the location of the CBE line which is slightly more than halfway between the SV and TV loads. The shape of the dynagraph indicates that the pump is filling properly.

As can be seen in the above information, pumping system analysis requires some thought and effort. But the rewards will be great for the owner of the wells and the individual who can do the analysis. A regular program of well monitoring and analysis is

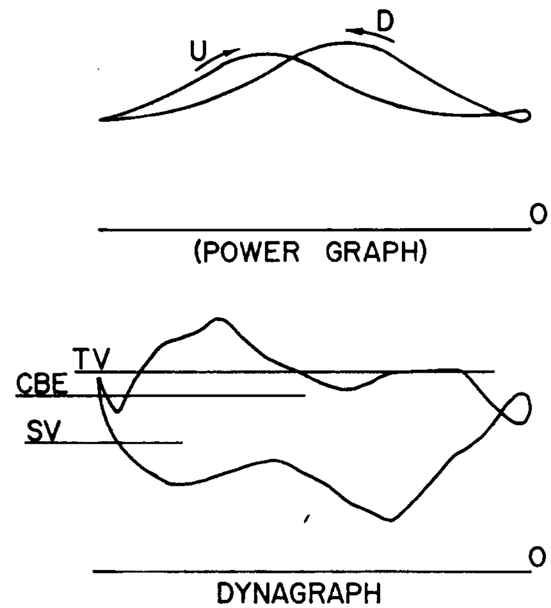


FIG. 6 TYPICAL DYNAGRAPH AND POWER GRAPH

an immediate way for increased profits both in reduced well down-time, which results in increased production, and in reduced maintenance costs.

Equipment is now available that will allow the analyst to obtain the necessary data quickly. Also, hand-held computers and their programs are available which will allow the analyst to make all of the necessary calculations on site. This equipment and analysis can reduce, tremendously, the time between the suspicion that a well has problems and its correction.

## BIBLIOGRAPHY


1. API RP11L API Recommended Practice for Design Calculations for Sucker Rod Pumping Systems (Conventional Units).
2. API BUL 11L2 API Catalog of Analog Computer Dynamometer Cards.
3. API SPEC 11B Specification for Sucker Rods.
4. API SPEC 11E Specification for Pumping Units.
5. API FORM No. 11L-1 Design Calculations for Conventional Sucker Rod Pumping Systems.

These documents can be obtained from

American Petroleum Institute
300 Corrigan Tower Building
Dallas, Texas 75201

# APPENDIX

## 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________________________________ Well Name________________________ Date____________

Field ________________________________ County ________________________ State____________

Required Pump Displacement, PD________________bbls./day  Maximum Allowable Rod Stress____________psi

Fluid Level, $H =$ ________ft.  Pumping Speed, $N =$ _____SPM  Plunger Diameter, $D =$ ______in.

Pump Depth, $L =$ ________ft.  Length of Stroke, $S =$ _____in.  Spec. Grav. of Fluid, $G =$ ______

Tubing Size_____in. Is it anchored? Yes, No  Sucker Rods ______________________________

**Record Factors from Tables 1 & 2:**

1. $W_r =$ ____________(Table 1, Column 3)
2. $E_r =$ ____________(Table 1, Column 4)
3. $F_c =$ ____________(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 ______ = ______lbs.
6. $1/k_r = E_r \times L =$ ________ x ________ = ____________in/lb.
7. $Sk_r = S \div 1/k_r =$ ______ ÷ ________ = ________lbs.
8. $F_o/Sk_r =$ ________ ÷ ________ = ________
9. $N/N_o = NL \div 245{,}000 =$ _____ x ______ ÷245,000 = ______
10. $N/N_o' = N/N_o \div F_c =$ ________ ÷ ________ = ________
11. $1/k_t = E_t \times L =$ ________ x ________ = ________in/lb.

**Solve for $S_p$ and PD:**

12. $S_p/S =$ ______(Figure 2)
13. $S_p = [(S_p/S) \times S] - [F_o \times 1/k_t] =$ [______ x ______] - [______ x ______________] = ________in.
14. $PD = 0.1166 \times S_p \times N \times D^2 = 0.1166 \times$ ______ x ______ x ______ = ________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 ________ = ________lbs.
16. $W_{rf} = W[1 - (.128G)] =$ ________ [1-(.128 x ______)] = ________lbs.
17. $W_{rf}/Sk_r =$ ________ ÷ ________ = ________

**Record Non-Dimensional Factors from Figures 3 through 7:**

18. $F_1/Sk_r =$ ________(Figure 3)
19. $F_2/Sk_r =$ ________(Figure 4)
20. $2T/S^2k_r =$ ________(Figure 5)
21. $F_3/Sk_r =$ ________(Figure 6)
22. $T_a =$ ________(Figure 7)

**Solve for Operating Characteristics:**

23. $PPRL = W_{rf} + [(F_1/Sk_r) \times Sk_r] =$ ________ + [________ x ________] = __________lbs.
24. $MPRL = W_{rf} - [(F_2/Sk_r) \times Sk_r] =$ ________ - [______ x ________] = __________lbs.
25. $PT = (2T/S^2k_r) \times Sk_r \times S/2 \times T_a =$ ______ x ________ x ______ x ______ = __________lb inches
26. $PRHP = (F_3/Sk_r) \times Sk_r \times S \times N \times 2.53 \times 10^{-6} =$ ______ x ________ x ______ x ______ $\times 2.53 \times 10^{-6} =$ __________
27. $CBE = 1.06(W_{rf} + 1/2\ F_o) = 1.06 \times$ (__________ + __________) = __________lbs.