Gear Boxes, Counterweights, Pumping Uuits and Dynamometers

By JAMES A. KLOTZ
The Pure Oil Company

INTRODUCTION

At first thought, oil well pumping systems appear to be very simple devices. Indeed, in shallow wells the operation of the sucker rod, the pump, the walking beam, and the gear box is simple and straightforward. But no one who has worked with deep well pumps needs to be told that in these wells the simple sucker rod system becomes extremely complicated. Most of the complication arises in the sucker rod, which is the part of the system that at first thought appears to be the simplest. Yet in a deep well the sucker rod ceases to act like a simple solid bar and begins to act more like a rubber band. Detailed study of the sucker rod requires thorough knowledge of theories of elasticity, vibration analysis, and wave propagation through solid materials.

The complicated series of forces arising in the sucker rod-pump system play upon the parts of the pumping unit. This unit also appears to be a relatively simple device. Yet, on closer examination, the walking beam, pitman, and crank link together in a way that reacts subtly upon the sucker rod. At the driving end of this system lies the gear box. Probably this is the most expensive item in the entire system, and it is the item that is most difficult to change once it has been installed. Thus, there is considerable incentive to design the gear box correctly in the first place. Because of cost, there is considerable incentive to determine ways of using the smallest possible gear box. This paper will explore some of the ways that a pumping unit installation can be varied in order to change gear box torque.

DESCRIPTION OF STANDARD WELL

For the purpose of this discussion we will consider one typical well. The statements that are made here are believed to be general and can be applied to any well. These ideas often are easier to visualize if they are presented in terms of a specific well. Table 1 presents the main features of this well. It is a somewhat average well. It is not extremely deep; neither is it a shallow well. The production rate, which is presumed to be part oil and part water is fairly high, but not extreme. The well operates with a 160,000 in.-lb pumping unit.

TABLE 1

DESCRIPTION OF STANDARD WELL

Description	
Depth	4100 ft
Production rate	200 B/D
Average liquid specific gravity	0.94
	58.6 pcf
Tubing	2-1/2 in.
Tubing anchored at	4100 ft.
Net lift	4100 ft.
Sucker rods	3/4 in.
Polish rod stroke	48 in.
Pumping speed	15 span
Pump plunger diameter	1-3/4 in.
Peak polish rod load	14,000 lbs.
Resonant pumping speed	59.9 spm
Dimensionless pumping speed	0.25
Dimensionless liquid load on sucker rod string	0.30

In order to examine other pumping configurations for the same well, the liquid loading on the sucker rods and the pumping speed can best be described in the dimensionless units that are shown as the last items in Table 1. The dimensionless pumping speed is the ratio of the actual speed, 15 spm, to the speed at which the sucker rod string will resonate, 59.9 spm. At resonant speed a standing wave motion will reside in the sucker rod. Forces at the pump will be low, but the pump travel will be many times greater than the length of the polish rod stroke. Conversely, at the polish rod end of the rod string rod displacement will be low, but forces will be so high that the rod string would break immediately. Obviously we cannot operate in resonant condition. This speed forms a convenient reference point. Rod strings operating at the same fraction of resonant speed will exhibit the same dynamic behavior regardless of actual pumping speed. Thus, the 4100 ft well operating at 15 spm will exhibit the same sucker rod dynamics as a well 8200 ft deep operating at 7.5 spm, or a 2050 ft well at 30 spm.

The dimensionless liquid loading on the rod string depends upon the diameter of the sucker rods, length of the rods, length of the polish rod stroke, and the weight of the liquid column lifted by the rods. The dimensionless loading is the ratio of weight of the liquid column to a weight that would stretch the rods for a distance equal to the polish rod stroke length. In the standard well, a load of about 13,000 lbs applied to the bottom end of the 4100 ft of 3/4 in. sucker rods would stretch these rods 48 in., the length of the polish rod stroke. A smaller diameter rod string would require a smaller force to stretch this distance, and conversely, a larger diameter string would require a greater force. The weight of the 4100 ft fluid column lifted by the 1-3/4 in. pump plunger in this standard well is about 4000 lbs. Use of a larger plunger would, of course, increase the weight of the fluid column; a smaller plunger would decrease this weight. For this well, the dimensionless liquid loading on the rod string is the ratio of the 4000 lb liquid load to the 13,300 lb loading required to stretch the rod string; this ratio is 0.3.

The significance of this dimensionless rod loading can be visualized by consideration of a pumping system operating at very low speed. At low speed, the rod stretch due to the liquid load will be equal to the product of dimensionless loading and the polish rod stroke length. Thus, for the standard well at a dimensionless loading of 0.3 and polish rod stroke of 48 in. the rods will stretch about 14.4 in. each time the traveling valve picks up the fluid load. The resulting pump plunger motion, then, will be 48 in. less 14.4 or about 33.6 in. For a very low dimensionless loading the pump stroke will almost equal the polish rod stroke, and for a high dimensionless loading, approaching unity, almost all of the polish rod stroke will be used to stretch the rods.

The two dimensionless variables, dimensionless speed and dimensionless loading, can be used to furnish a complete description of the static and dynamic forces in the sucker rod string. All wells with the same dimensionless loading and speed will operate in the same way regardless of the depth in feet, the rod diameter in inches and the pumping speed in strokes/minute. This statement presumes that the wells are in similar mechanical condition: that rod friction is about the same and that the pumps operate efficiently.

CHANGES IN SUCKER ROD SYSTEM

The pumping unit system for this standard well can be changed in either of two ways: the sucker rod system can be changed, or the pumping unit can be changed. Changes in the slcker rod system can be discussed in terms of changes in the dimensionless pumping speed and in changes in dimensionless liquid loading on the rod string.

The previous section stated that all wells operating with the same dimensionless parameters will operate in the same way. Also, it is true that the same well can be pumped with a wide range of dimensionless parameters. For this well, the 4100 ft depth and the 200 B/D production rate will be retained. Then the dimensionless pumping speed can be changed within the range of 0.[illegible] to 0.6, and the dimensionless liquid loading on the rods can be changed through the range of 0.[illegible] to 0.7. These changes are accomplished by changing stroke length, rod diameter, and plunger diameter. Conditions for several dimensionless parameters are shown in Table II. This table represents sucker rod, pump and stroke length configurations that will pump 200 B/D from a depth of 4100 ft. Some of the configurations may not be available commercially, but they are at least within the range of commercially available equipment. At low speeds, 6 spm, pump stroke must be increased considerably in order to obtain the 200 B/D production rate; high pumping speeds achieve this production rate with a relatively short stroke. Changes in dimensionless loading are achieved by changing the plunger diameter and the rod diameter. Large rods are stiffer; thus for the same liquid load the ratio between liquid load and stretch is less. The dimensionless liquid loading of 0.7 represents a heavily loaded rod string; this is achieved only through the use of 5/8 in. diameter rods and large plunger diameters. Probably this represents a situation in which the rod string would be stressed too much. Yet this condition will be retained for the insight that it might give.

TABLE II

PUMP SPEED, PLUNGER DIAMETER, STROKE LENGTH FOR DIFFERENT DIMENSIONLESS PARAMETERS

Well Depth 4100 ft. Production Rate 200 B/D

Pump Speed		Rod Loading, Dimensionless		
Dimensionless	Spm	0.1	0.3	0.7
0.1	6	1.73 plunger 104. stroke 7/8 rods	2.25 80. 3/4	3.08 92.5 5/8
0.25	15		1.75 plunger 48 stroke 3/4 rods	
0.5	30	1.05 plunger 38.2 stroke 7/8 rods	1.33 27.5 3/4	1.66 26.5 5/2
0.6	36		1.2 plunger 23. stroke 3/4 rods	

Plunger diameter, stroke length, and rod diameter is in inches.

Fig. 1 shows the shapes of the dynamometer cards that will result from the use of these varied liquid loadings and pump speeds. Low speed, dimensionless parameter of 0.1, results in dynamometer cards that are almost ideal parallelograms. Low loading results in a low wide card, and high loading results in a tall thin card. Increased pumping speeds bring increased dynamic effects into play and the card form loses its regularity, until at high speed, dimensionless parameter of 0.6, the card is irregular indeed.

Particular attention should be given to two values that can be determined from these dynamometer cards: the position along the length of the card at which the peak rod load occurs, and the magnitude of this rod load. Note, for example, that the peak rod load for pump speed of 0.1 and liquid load of 0.1 occurs very near to the left-hand end, the bottom end, of the card; whereas for a speed of 0.1 and a loading of 0.7, the peak loading occurs very near the right end of the card. This position of the peak rod load has a great influence on the torque developed in the gear box by this load. Table III summarizes the peak loads and the positions of these loads. In this table peak polish rod loadings are stated in

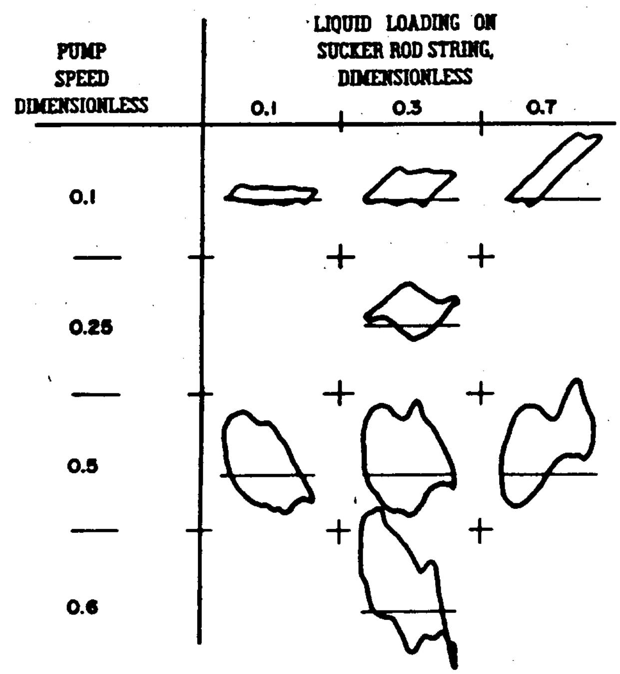

Figure 1

Dynamometer Card Shape For Varied Pump Speed And Ror Loading

TABLE III
PEAK POLISH ROD LOAD AND POSITION OF LOAD

Pump Speed Dimensionless	Liquid Loading On Sucker Rod String, Dimensionless 0.1	0.3	0.7
0.1	15.6 M lbs 0.131	15.6 M lbs 0.376	19.7 M lbs 0.746
0.25		14.0 M lbs 0.466	
0.5	13.5 M lbs 0.205	14.0 M lbs 0.588	15.0 M lbs 0.801
0.6		15.4 M lbs 0.160	

Note: The upper number for each speed and each dimensionless loading is the rod load in thousand of lbs; the lower number is the polish rod position at which the peak rod load occurs. Position ranges from 0.0 at the bottom of the polish rod stroke to 1.0 at the top of the stroke.

thousands of pounds and the position is stated as a fraction ranging between 0.0 at the bottom of the polish rod stroke and 1.0 at the top of the stroke.

With the range of rod diameters, plunger diameters, pumping speeds, and polish rod stroke lengths described in the immediately preceding paragraphs and in Table II, the well will pump 200 B/D of liquid. The dynamometer cards vary widely for this range of conditions; the peak polish rod load occure at positions ranging between 0.13 and 0.80. Rod load in pounds does not change much from 15,000 lbs, except for one pumping condition, but the dimensionless loading changes between 10 per cent and 70 per cent of the loading required to stretch the rod string a distance equal to the polish rod stroke.

Now the question arises: how can we take advantage of these changes and of the position at which the peak polish rod load occurs to reduce gear box torque?

POLISH ROD POSITION

Polish rod load generates gear box torque. The previously mentioned standard well is pumped at a dimensionless speed of 0.25 and with a dimensionless loading of 0.3. Assume that the well is pumped with a regular square pumping

TABLE IV
TYPICAL PUMPING UNIT DIMENSIONS

Dimensions	Regular-Square Unit	Regular-Long Unit	PushUp-Square Unit	Push Up-Short Unit
Beam	3.75	3.75	4.37	4.37
Saddle Bearing to Horsehead	1.87	1.87	2.5	2.5
Saddle Bearing to Tail Bearing	1.87	1.87	1.87	1.87
Crank	0.495	0.448	0.374	0.365
Stroke	1.0	1.0	1.0	1.0
Pitman	1.73	1.65	1.72	1.65
Saddle Bearing to Crank Center				
Vertical	1.65	1.65	1.65	1.65
Horizontal	1.87	2.36	1.87	1.5

Note: Pumping unit dimensions are given in terms of stroke length. For the Square units distance between the saddle bearing and the tail bearing is the same as the horizontal distance between the saddle bearing and the crank center. For the Regular Long and the Push Up Short units the crank center has been moved so that the pitman is approximately vertical, and the crank horizontal at mid stroke.

unit; that is, a pumping unit with the samson post situated between the crank and the well. The word "square" indicates that the distance from the saddle bearing to the tail bearing is the same as the distance from the saddle bearing to the horsehead, and that the horzontal distance between the saddle bearing and the crank centeris equal to the distance between the saddle bearing and the tail bearing; that is the crank center is immediately under the tail bearing when the beam is horizontal. Also, the crank is horizontal pointing toward three o'clock when the beam is horizontal. Typical dimensions of such a unit are shown in Table IV.

The regular square pumping unit can be characterized by a torque factor curve as shown in Fig. 2 The numbers plotted on this curve are similar to the standard torque factors that are published for pumping units by each unit manufacturer. The torque factors are divided by a number equal to 1/2 of the stroke length. Thus, the curves on Fig. 2 might be expected to have a peak value for upstroke and downstroke torque factors of about 1.0. Note, however, that the regular square unit has a peak torque factor about 1.05 and that this peak occurs at a polish rod position of about 0.39. The torque factor in excess of 1.0 indicates that there is some multiplication of torque through the linkages in the pumping unit and that, at the peak, the polish rod load is effective for torque generation at a lever arm that is about five per cent greater than 1/2 of the stroke.

The calculation of gear box torque is achieved by multiplication of torque factor and peak polish rod load; the resulting torques are plotted on Fig. 3. This figure also contains a reproduction of the dynamometer card, the counterweight torque, and resulting net torque for this well. The polish rod load plotted here is divided by the peak polish rod load so that this graph runs through a range of 0 to 1.0. The dynamometer card is plotted in two ways: first, as a conventional closed loop, and second, with the bottom half of the curve folded out so that it can be compared with the downstroke torque curve. The torque that is plotted on this figure is a dimensionless torque. The numbers are derived by dividing the crank torque, measured in inch-pounds, by the product of the peak polish rod load and I/2 of the stroke length. Thus, for the standard well the peak torque caused by polish rod load is 346,500 in-lbs at a stroke of 48 in. An ideal peak torque might be considered to be the product of the peak polish rod load of

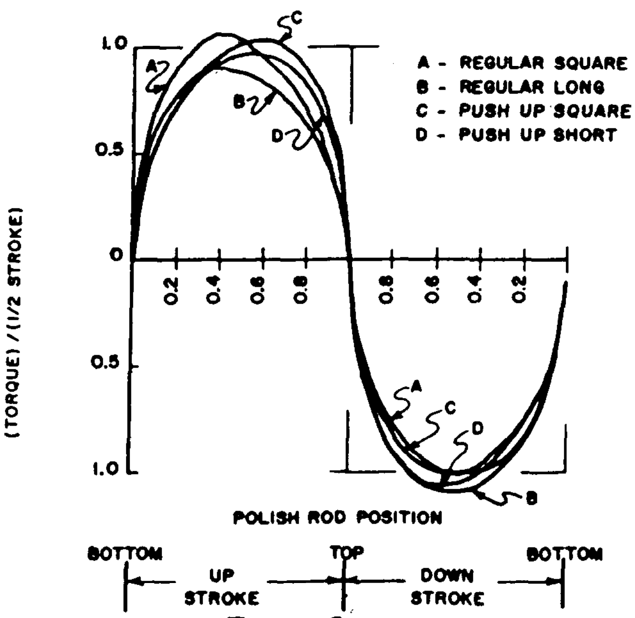

Figure 2

Pumping Unit Torque Factors

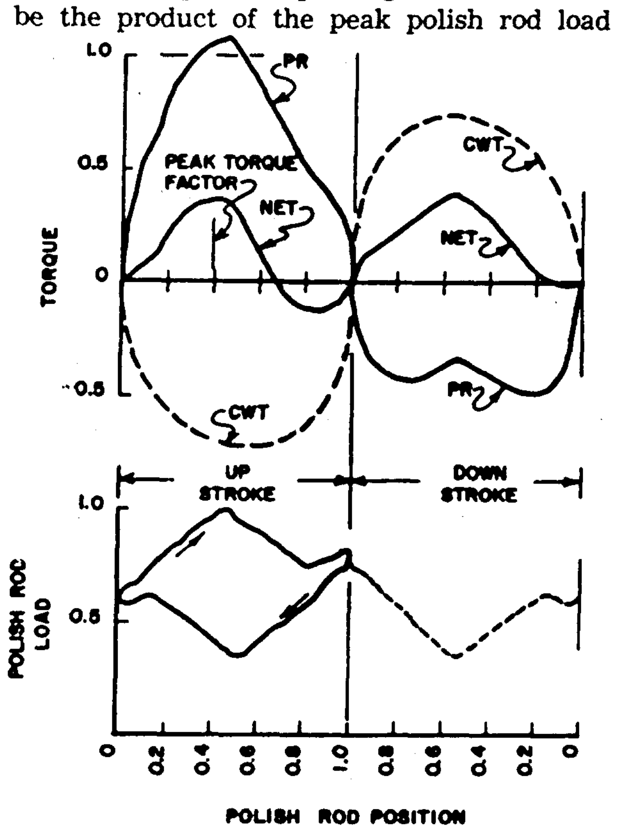

Figure 3

Regular Square Unit Loading-0.3; Speed-0.25

13,800 lbs and 24 in., or 331,500 in.-lbs. The 346,500 in.—lbs torque is 5 per cent greater than this and plots as the number 1.05 on Fig. 3.

The vertical line in the torque graph on Fig. 3 indicates the polish rod position, 0.39, at which the peak torque factor occurs for a regular square unit. Note that this position is very close to the position at which the peak polish rod load occurs, 0.47. Thus, torque factor and polish rod load both are high at the same time. The net result of this is a fairly steep shape to the curve that represents the torque generated by the polish rod load.

The torque generated by counterweights also is plotted on Fig. 3. The counterweight has been chosen at 9800 lbs (polished rod effect) so that the net peak gear box torque on upstroke will equal the net peak gear box torque on downstroke. The net torque curve also is plotted on Fig. 3. The peaks of this curve are at a torque of about 0.36.

As the torque curves on Fig. 3 are examined in order to determine what might be done in order to reduce the net gear box torque, several things come to mind. If a pumping unit-sucker rod combination can be developed so that the peak torque factor for the pumping unit and the peak polish rod load do not occur at the same polished rod positoin, the resulting polish rod torque curve will be flatter and not as high as the curve on Fig. 3. Then, too, if the pumping unit can be changed so that the peak upstroke torque curve from the polish rod is more nearly equal to the peak downstroke curve from the polish rod, these peaks can be counterbalanced to a lower net torque curve. In order to do this, we can consider pumping this well with different dimensionless loadings, at different dimensionless pumping speeds and with different kinds of pumping units.

We have considered three other pumping units in addition to the regular square unit. The dimensions of these other units are shown in Table IV. The second unit is a regular unit; that is the samson post is between the crank and the well. Except, for this unit, which I have named "regular-long" unit, the crank center has been moved away from the well by a distance approximately equal to the crank length. For this unit, the angles, at mid-stroke, between the beam and pitman and between the pitman and the crank are both right angles. Thus, we might expect a lower upstroke torque factor for this unit than for the regular square unit. The third pumping unit considered is designated as a "square push up" unit. For this unit the crank is located between the samson post and the well the horizontal distance between the saddle bearing and the tail bearing and between the saddle bearing and the crank center are equal. For this unit, as well as for the regular square unit, the crank center is immediately under the tail bearing when the beam is horizontal. The fourth unit considered is similar to the square push up unit except that the crank center has been moved toward the samson post by a distance approximately equal to the crank length. For this unit the angles formed by the beam and the pitman and by the pitman and the crank at midstroke are right angles. The short push up unit is analogous to the long regular unit; both of these might be expected to have lower torque factors at the middle of the upstroke than either the regular square unit or the push up square unit. Fig. 2 shows the torque factor curves for these units. Table V summarizes this information by showing the peak factor and the polish rod position at which this peak torque factor occurs. From the viewpoint of this analysis, the regular long unit appears to offer the greatest potential for reduction of upstroke torque and increase of downstroke torque. On the other hand, the torque peak for the square push up unit occurs well above the mid point of the stroke, so that this unit might be used advantageously with a dynamometer card in which the peak polish rod load occurs at a low polish rod position.

MOST EFFECTIVE PUMPING UNIT-SUCKER ROD COMBINATIONS

We now are in a position to examine the effects of combining these different pumping unit configurations and sucker rod configurations. Fig.4 shows the resulting torques calculated for the standard well when it is pumped with a regular long unit. An examination of this figure along with Fig. 3 shows that the peak torque caused by polish rod load has been decreased from about 1.05 to 0.89 and that the peak net torques for upstroke and downstroke have been decreased to about 0.30, a reduction of 20 per cent. Note, however, that the peak torque factor for the regular long unit occurs at exactly the same spot as the peak polish rod load for this well. All of the torque factor reduction that is experienced comes about as a result of reduction in the upstroke torque factor. No gain may have

TABLE V

PEAK TORQUE FACTOR AND POSITION OF PEAK

Unit Type	Up-Stroke Peak Factor	Up-Stroke Position	Down-Stroke Peak Factor	Down-Stroke Position
Regular-Square	1.05	0.39	1.00	0.54
Regular-Long	0.895	0.43	1.10	0.54
Push Up-Square	1.03	0.57	1.005	0.54
Push Up-Short	0.98	0.55	1.08	0.57

Torque factor is shown here as Unit Torque factor/(1/2 stroke)

Position = 0.0 at bottom of stroke
Position = 1.0 at top of stroke

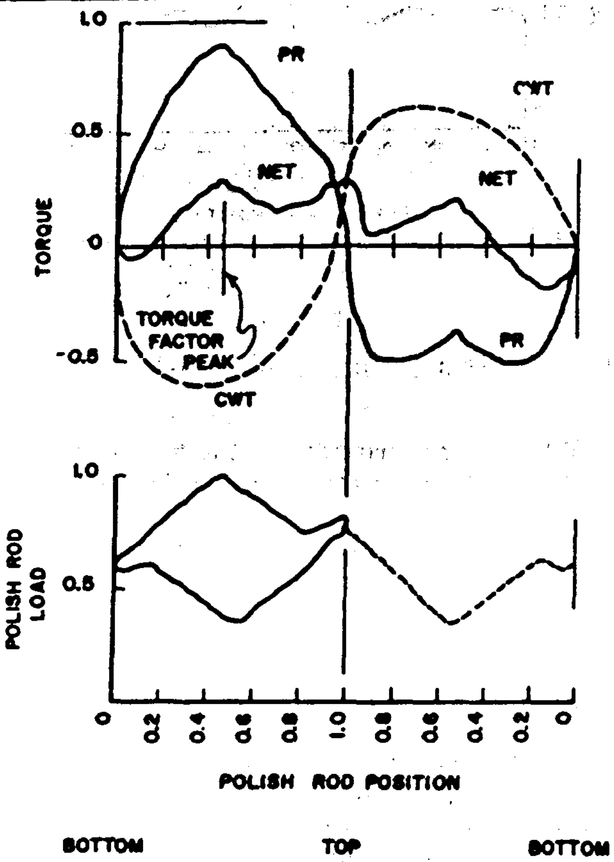

Figure 4
Regular Long Unit Loading-0.3; Speed-0.25

been made by changes in the relative position of the peak torque factor and the peak polish rod load.

In order to determine what benefits might be gained by judicious positioning of the peak polish rod loads and the peak pumping unit torque factors, examine the dynamometer cards on Fig. 1 and the torque factor positions shown in Table V. Try to find a combination for which the peak polish rod load appears at a widely different polish rod position than the peak torque factor. Several possible combinations present themselves on first examination. The first of these combinations might include a sucker rod string operating a dimensionless loading of 0.1 and a speed of 0.1. For this combination, the peak polish rod loading occurs at a polished rod position of about 0.13. The pumping unit whose peak upstroke position factor is separated most widely from 0.13 is the push up square unit where, see Table V, the peak upstroke torque factor occurs at 0.57. The resulting polish rod torque and counterweight torques are shown on Fig. 5. The net torque is as low as 0.20. Note, again, that this low net torque is not caused by the low profile of the dynamometer card that appears on Fig. 1. These figures are not drawn to scale. This figure indicates card shapes more than exact dimensions; polish rod load peaks are nearly 15,000 lbs for most of the dynamometer cards on Fig. 1.

Another possible rod-pumping unit combination might be the combination of a sucker rod string operating at a loading of 0.3 and a speed of 0.1. For this sucker rod, the peak polish rod load occurs at a polish rod position of 0.38; this is still considerably removed from the peak torque factor position for the push up units. Fig. 6 shows the resulting torque for a square push up unit; peak net torque is 0.24.

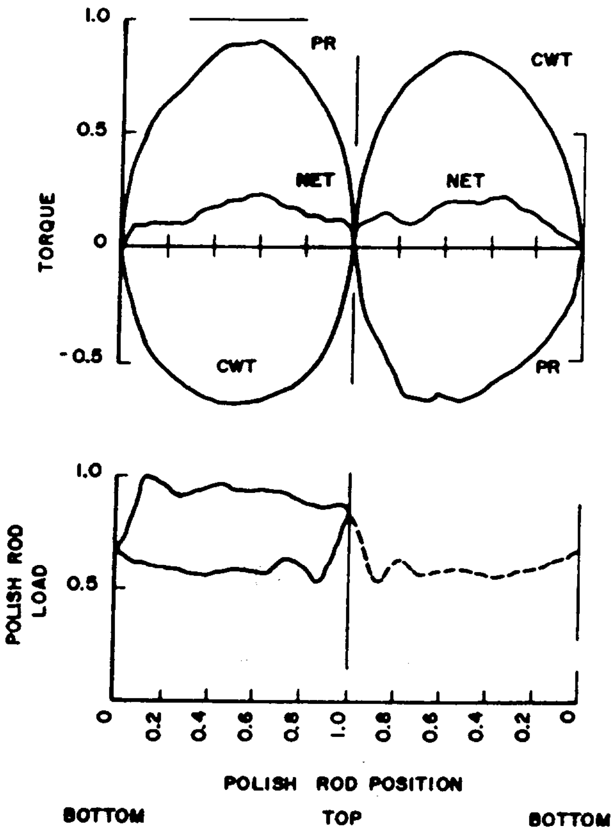

Figure 5

Push Up Short Loading Unit-0.1; Speed-0.1

Another possible combination is a sucker rod string operating with a loading of 0.7 at a speed 0.5; this might be used with a regular long unit. The peak polish rod load for this rod occurs at a rod position of 0.8, and the peak torque factor for a regular square unit occurs at a position of 0.39. Because these two positions are fairly far removed from each other we might expect that this combination would have a low net torque. The torques are plotted on Fig. 7. Note that the polish rod torque at the peak polish rod load is indeed fairly low. A secondary polish rod load peak, occurring at a position of 0.35, is very close to the torque factor peak; this secondary load peak causes high torques so that the net resulting upstroke torque is 0.3.

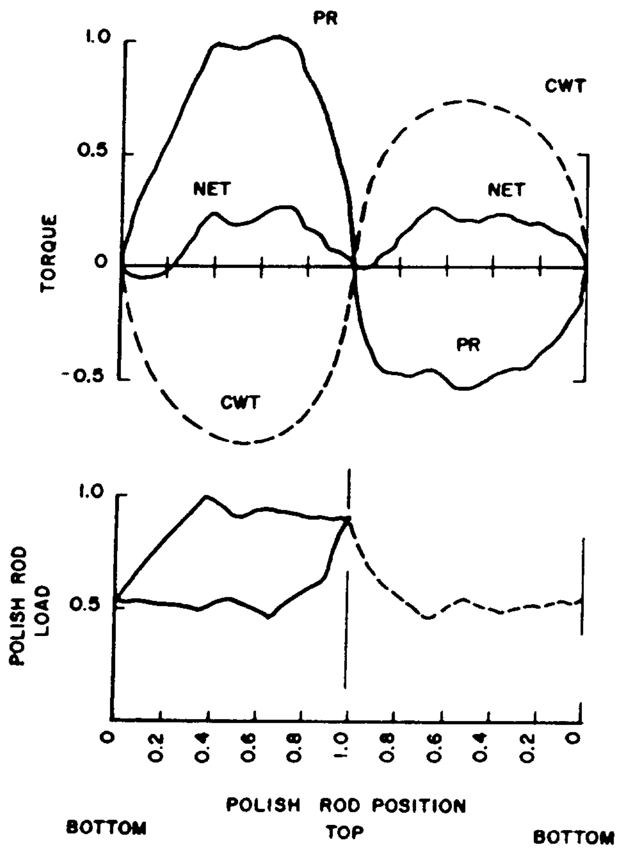

Figure 6

Push Up Square Unit Loading-0.3; Speed-0.1

Table VI summarizes all of the net torques for various combinations of sucker rods and pumping units. Examination of this table shows that the dimensionless torques for these combinations range from 0.2 to 0.43. The minimum value of 0.2 occurs with a push up square unit operated at a 0.5-0.1 speed loading combination. The maximum value of 0.43 occurs for a similar unit operated at a speed of 0.5 and a loading of 0.3.

All of these torques calculations are for the same well: this standard well producing 200 B/D of fluid from a depth of 4100 ft. The difference between poor selection of a pumping unit sucker rod combination and a good selection of a pumping unit sucker rod combination is a two-fold difference in torque factor.

TABLE VI
NET PEAK TORQUE
FOR
COMBINATION OF SUCKER RODS
AND
PUMPING UNITS

Pump Speed	Rod Loading Dimensionless		
Dimensionless	0.1	0.3	0.7
0.1	0.34	0.39	0.22
	0.21	0.24	0.36
	0.20	0.25	0.34
0.25		0.36	
		0.29	
		0.33	
		0.33	
0.5	0.42	0.41	0.30
	0.35	0.40	0.30
	0.35	0.43	0.40
	0.35	0.43	0.37
0.6		.35	
		.31	
		.31	
		.31	

Note: All torques in this table are reported as dimensionless torques; that is pumping unit torque, measured in inch pounds, divided by the product of peak polish rod load and 1/2 of the stroke. For each rod loading and speed combination four torque numbers are shown for four different pumping units. These are

1. Regular-Square Unit
2. Regular-Long Unit
3. Push Up-Square Unit
4. Push Up-Short Unit

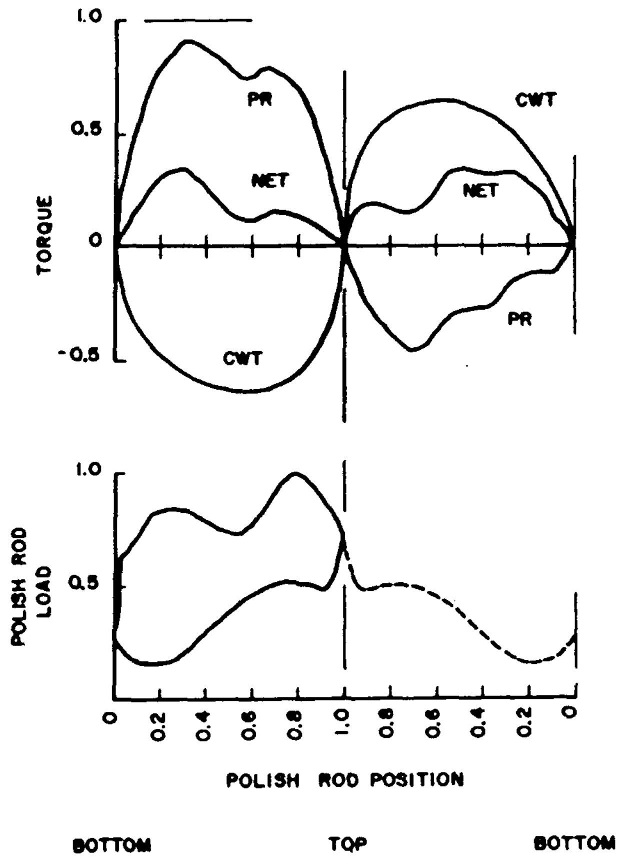

Figure 7
Regular Square Unit Loading-0.7; Speed- 0.5

CONCLUSIONS

The sucker rod-pumping unit system for lifting oil from wells is indeed a complicated system, and it is difficult to analyze this system in full detail. Yet, certain insight into operation can be gained by examining parts of the system. Gear box torque is the result of at least two factors: (1) the magnitude of the polish rod loading and the torque factor for the pumping unit, and (2) the relative positions of the peak torque factor and the peak polish rod loading. Some improvement can be gained through the use of pumping units that are arranged to give low torque factors. The regular long unit appears to deliver the lowest peak torque factor. Even more benefit may be gained by judicious selection of the position of the peak torque factor and the peak polish rod load. The difference between a good combination and a bad combination of pumping unit and polish rod system may be a twofold difference in the torque rating of the gear box.