Using Sucker Rods To Lift Large Fluid Volumes

By J. P. BYRD

Lufkin Foundry & Machine Company

A century ago the almost universal mechanism for artificially lifting fluid in an oil well was the standard rig-front. A wooden walking beam drove a string of hickory sucker rods, often called "well poles", as many as ten — 12 to 15 in. strokes per minute with the maximum tensile stress of the rods around 12,800 psi. The bottom-hole pump was of the cast iron or brass variety with approximately 1-1/4 in. diameter barrel, and the well depth ranged from 500 ft to 1000 ft. The torque capacity of the band wheel and flat-belt speed reducer ran only several thousand in.-lbs., and the unit's structural capacity was in the neighborhood of 1000-1500 lbs.

Today, the structure of a modern pumping unit with its 240-in. maximum stroke reaches higher than the wooden drilling and servicing derricks of those early days; its structural capacity exceeds 47,000 lbs., with a torque rating greater than 2,500,000 in.-lbs. The plunger diameter of some recent bottom-hole pumps (casing-type) runs as high as 5-3/4 in. Perhaps the greatest improvement is that of the sucker rod which now has a tensile stress of some 140,000 psi. Today's practical sucker rod pumping approaches 13,000 ft. and capacities of 5 and 6000 BPD from shallow to medium depths are handled with ease. Volumes as high as 9500 BPD are entirely practical with modern sucker rod pumping equipment.

Comparing today's sucker rod system with its counterpart of 100 years ago produces some startling figures. The structural capacity of the modern unit has increased nearly fifty-fold, the torque capacity perhaps 1000-fold; the area of the bottom-hole pump has increased over 20 times; the stroke length has risen nearly twenty-fold, while maximum rod tensile stress has increased nearly 12 times. With the increased stroke length, even the maximum amount of polished rod travel per minute has increased five or six times. Since all of these increases are of the compounding variety, it can be readily seen that the sucker rod pumping unit of today has the capacity for producing massive fluid volumes from relatively great depths.

GENERAL

The ability of a sucker rod pumping system to produce fluid (assuming relatively incompressible fluid) is limited by one or more of the following: (1) the unit's stroke length, (2) the maximum rate of rod fall for a given well, (3) the plunger diameter of the bottom-hole pump, (4) the strength of the sucker rods, and (5) the unit's torsional and structural capacity, and to a slight degree, its geometry. Pumping unit geometry, stroke length and rod retarding forces also control maximum pumping speed to a slight degree; the chief variable being the crank-to-pitman ratio C/P. On a conventional unit, the lower the C/P ratio, the higher the critical pumping speed. On Class III units (Mark II and air balance), just the reverse is true — the higher the C/P ratio, the higher the critical pumping speed.

A brief discussion of these items should be helpful for gaining a thorough understanding of high volume sucker rod pumping.

STROKE LENGTH AND MAXIMUM ROD FALL

Critical pumping speed has been defined as that speed on a given well (under a fixed set of normal pumping conditions), where the carrier bar just begins to leave the rod clamp during the downstroke. Stated another way, it is the lowest pumping speed at which the minimum polished rod load (downstroke) becomes zero.

Throughout this discussion constant angular velocity is assumed at the crankshaft of the pumping unit. Also the conventional Mills acceleration factor of $LN^2/70{,}500$ has been assumed. This is the maximum accelerative constant for simple harmonic motion, and, due to the machinery factor effect, varies considerably from the one which regular crank-pitman pumping unit geometry should actually employ.

For any given pumping unit geometry, critical pumping speed is controlled by two variables: (1) stroke length, and (2) well forces retarding rod fall, such as friction and buoyancy.

Table I shows the relationship between stroke length, critical pumping speed, and polished rod travel for the CONVENTIONAL PUMPING UNIT DROPPING RODS IN AIR. (This discussion considers only the symmetrical conventional unit, though other types of pumping unit geometry behave in a similar and proportionate fashion.) The stroke length range, from 64 in. to 168 in., is considered representative.

TABLE I

CRITICAL PUMPING SPEED — RODS IN AIR

Stroke Length (inches)	Critical Pumping Speed (strokes per minute)	Polished Rod Travel (feet per minute)
64	33	352
74	30.7	379
86	28.6	411
100	26.5	442
120	24.2	485
144	22.1	532
168	20.5	573

Table II illustrates the effect that the buoyancy of water has upon critical pumping speed — all frictional and other retarding forces are disregarded.

TABLE II

CRITICAL PUMPING SPEED WITH RODS FALLING IN WATER — WITH NO OTHER DOWNHOLE RETARDING FORCES

Stroke Length (inches)	Critical Pumping Speed (strokes per minute)	Polished Rod Travel (feet per minute)
64	31	331
74	28.7	354
86	26.6	382
100	24.6	410
120	22.4	449
144	20.6	495
168	19.1	537

By comparing Tables I and II, it can be seen what effect buoyancy has on limiting critical pumping speed and polished rod travel for a given stroke length.

Friction of all types (stuffing box, rod-to-fluid, rod-to-tubing, plunger, etc.) further limits rod fall, and unlike buoyant retarding forces, its effect is difficult, if not impossible, to predict until the well is actually drilled and pumping. These frictional forces vary from well to well and depend upon such things as crooked hole, plunger fit, paraffin conditions, stuffing box tightness, fluid viscosity, etc. A rule of thumb has been to assume that friction and buoyancy combine to limit rod fall to 70 per cent of its free fall in air. This is probably as good an approximation as any, but unless understood, can be misleading, for some wells have high forces of friction and retardation, while other wells give little opposition to the fall of the rods.

Table III shows the further limiting of critical pumping speed when rods are assumed to be retarded by buoyancy and friction to 70 per cent of their free fall rate.

TABLE III

CRITICAL PUMPING SPEEDS BASED ON 70% OF FREE ROD FALL RATE

Stroke Length (inches)	Critical Pumping Speed (strokes per minute)	Polished Rod Travel (feet per minute)
64	23	245
74	21.5	265
86	19.5	278
100	18.5	308
120	16.5	331
144	15	360
168	14	394

If buoyant and frictional forces of retardation are less than those shown in Table III (i.e. 70 per cent of free rod fall), greater critical pumping speeds can be achieved by the conventional pumping unit; if the forces of retardation are greater, lower maximum pumping speeds will result. (Retarding forces are considered to be independent of rod velocities.)

From Table I, it is evident that the maximum polished rod travel of the 64-in. unit (at its critical pumping speed) is 352 ft per minute (in air), while the 168-in. unit (at its critical pumping speed) would have a maximum polished rod travel of about 573 ft per minute — a dramatic increase in polished rod travel and pumping capacity due entirely to increased stroke length.

It is important to note that when operating at (or near) the critical pumping speed, total polished rod travel per minute can be increased by over 60 per cent simply by lengthening the stroke from 64 in. to 168 in.

It must be recognized that increasing stroke length will in turn increase torsional loading; but if maximum production is desired, the long-stroke unit greatly outperforms the short-stroke unit under ALL pumping conditions, regardless of geometry.

It is assumed that polished rod travel is directly proportional to pump travel, though harmonics and the elastic nature of the rod string may modify this to some slight extent.

MODERN SUCKER RODS

Since the beginning of the petroleum industry, it has been generally recognized that the limitation of sucker rod pumping is determined by the capacity of the sucker rod itself and with a significant increase in sucker rod strength, the maximum pumping capacity of the beam type unit can be substantially increased.

Perhaps the most dramatic improvement in any of the pumping system components has occurred in the field of sucker rod manufacturing technology. Within recent years a number of rod manufacturers have developed the quick-cycle quench-and-temper process which increases the sucker rod's working capacity significantly. Although this particular metallurgical technique has been known to manufacturers of high quality steel products for some time, it has been only in the past several years that this process has been applied to sucker rods. The use of this improved technique has enabled the rod manufacturer to produce a very fine grain needle-like structure in which the overlapping grains of the steel interrupt shear planes along which tensile failures would normally occur. This new method, compared to the former process of heat treating by normalizing, produces rods of superior performance. A sucker rod of the same chemical composition, heat treated by the new technique, has not only a much more refined micro-structure, but the steel is much tougher, its yield to tensile ratio has increased from about .56 to .91, and its resistance to fatigue has been significantly increased.

All else equal, the capacity of a bottom-hole pump to produce fluid is directly proportional to the amount of work that the surface unit can introduce into the polished rod. Since the amount of work that can be safely carried by a sucker rod string is directly proportional to its safe load range (difference between peak and minimum rod load), the new improved sucker rods with their greatly increased load range capacity can perform a significant amount of additional work per stroke, which, in turn, means additional fluid.

Comparing a standard API, Grade C rod with the new API Grade D high tensile rod, the two following examples illustrate the increased loading that the new rod can safely withstand, as well as an actual field study concerning cost savings.

Example 1

Pumping a certain well (under given conditions) with a straight string of 7/8-in. Class C rods driving a 1-1/4-in. diameter pump and a load ratio of .6, the maximum well depth, without overloading the rods, would be approximately 6000 ft. (Load ratio is the minimum polished rod load divided by the peak polished rod load). By using the new Class D rods—all else equal—an additional 4100 ft. of rods and fluid can be safely handled, thereby increasing the total pumping depth to 10,100 ft.

Example 2

For a given peak polished rod load, the load range of the Class D rod is considerably greater than that of the Class C rod. For instance, if the 7/8-in. Class C rod were loaded to its peak polished rod load of 25,918 lbs., its safe allowable load range would be 4268 lbs.

At the same peak polished rod load for the "D" rod, its safe allowable load range would be 17,642 lbs. This means that the "D" rod, in this particular case, has over four times the safe allowable load range as the "C" rod under the above conditions. With the fluid-handling capacity of the pumping unit being proportional to the load range, this means that the new rod could pump several times the total amount of fluid as the "C" rod and still not exceed its design capacity.

Field Study (Economic)

The economics of a sucker rod system is now made even more profitable as illustrated by a particular four-well application in Oklahoma which has an average depth of 11,900 feet per well. The improved sucker rods were used because they offered much greater yield strength (over a ton less weight) as well as resulting in a savings of about $1300 per well. Representative figures from this application are shown below:

	API Grade D Min. Yield 90,000 PSI		API Grade C Min. Yield 65,000 PSI	
Rod Size	1"	2250'	1-1/8"	1675'
and	7/8"	2625'	1"	1900'
Length	3/4"	7025'	7/8"	2150'
			3/4"	6165'
		11,900'		11,900'
Weight	23,500 Pounds		26,220 Pounds	
Peak Torque	388,000 lb/in		401,700 lb/in	
H.P.	29.36		31.39	
COST	$6750.00		$8050.00	

Savings of $1300.00 per Well*

*An estimated additional savings of $753.75 per well was achieved by reducing the larger tubing requirements of the 1-1/8" rods.

These three examples emphasize not only the increased load carrying capacity of the new improved rods, but their increased cost savings as well.

TORSIONAL AND STRUCTURAL CAPACITY OF A PUMPING UNIT

From a practical standpoint, there is little to limit the structural and torsional capacity of an oilfield pumping unit — other than rod strength. Although the modern pumping unit is compactly designed and constructed, still unit size limitations on the average lease are often of little consequence and pumping units of extreme size with enormous torque capacity are eminently practical. Today, one of the major pumping unit manufacturers builds a conventional unit (Fig. 1) having a stroke length of 192 in., a torsional capacity of 1,280,000 in-lbs., and a structural capacity of some 35,600 lbs. A Mark II line of units (Figs. 2 and 3) with 168-in. stroke, 912,000 in-lbs. gear reducer, and a 35,600-lb. structure is also available. 192-in. and 216-in. stroke Mark II's with 1,280,000-lb boxes are currently being produced. The largest sucker rod pumping unit, however, is of the air balance variety, having a maximum stroke length of 240 in., a torsional capacity of 2,560,000 in-lbs., and a structural capacity of over 47,000, (Fig. 4).

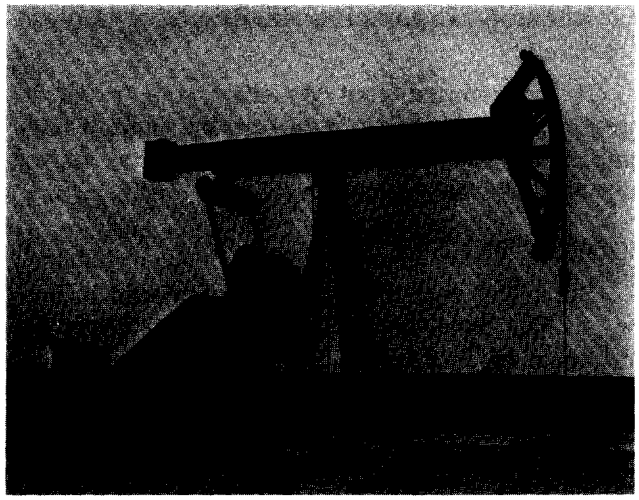

FIGURE 1

Conventional unit having a structural rating of 35,600 lbs. and a pumping stroke of 168 in, operating in West Texas.

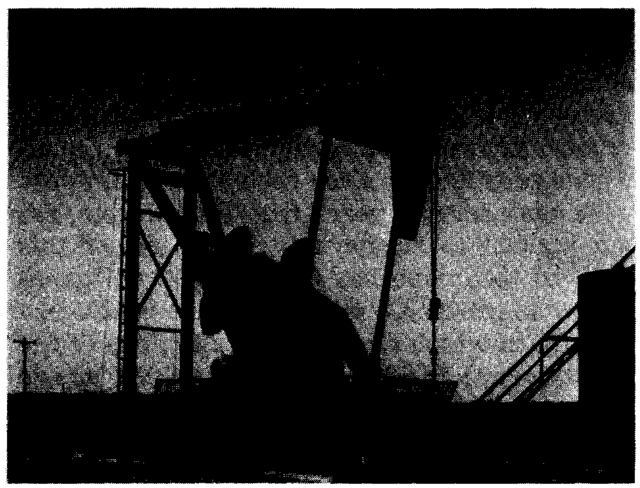

FIGURE 2

This Mark II unit with 144 in. stroke, 320,000 in.lbs. reducer and 5-3/4 in. casing pump has lifted as much as 5,860 bbls. per day pumping 13 SPM.

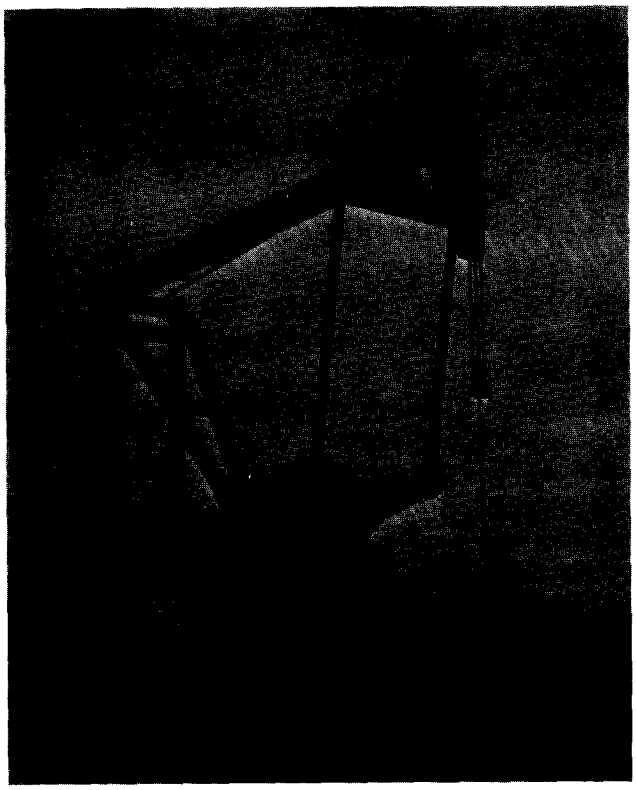

FIGURE 3

A Mark II operating in North Central Texas and lifting approximately 4000 BPD with a 640,-000 in.-lb reducer and 120 in. stroke.

INCREASED BOTTOM-HOLE PUMP CAPACITY

Another significant advance in sucker rod driven pump design was the introduction, several years ago, of the two-stage bottom-hole pump. It is especially desirable when large volumes of fluid must be lifted, and is particularly applicable to water-drive wells and waterflood operations. This is an insert type pump and permits the entire subsurface pumping equipment to be pulled with the rods. The two-stage pump with 1-1/2-in bore produces over 65 per cent more fluid than an equivalent insert pump, and over 20 per cent more fluid than a similar tubing pump. The largest two-stage pump is the 2-1/2-in. bore (for 3-in. tubing) and produces proportionately more fluid than its opposite numbered insert and tubing pumps.

For many years a 4-3/4 in. bore tubing pump has been available to the industry, and casing pumps are now manufactured in diameters as large as 5-3/4 in. Both of these large bore bottom-hole pumps, driven by long-stroke surface units, are capable of producing massive fluid volumes.

Recently, one of the major manufacturers developed a revolutionary new sucker rod driven bottom-hole pump that, in many cases, can increase pump capacity by a substantial amount. This new pump has a special ring valve near the top of its housing which isolates the weight of the fluid column from the traveling valve during the downstroke. This ring valve acts as a check valve at the bottom of the fluid column. Additionally, this new pump has a much larger intake flow area than the standard pump, offering little or no restriction to incoming fluid. The valves are also closely spaced for minimum dead

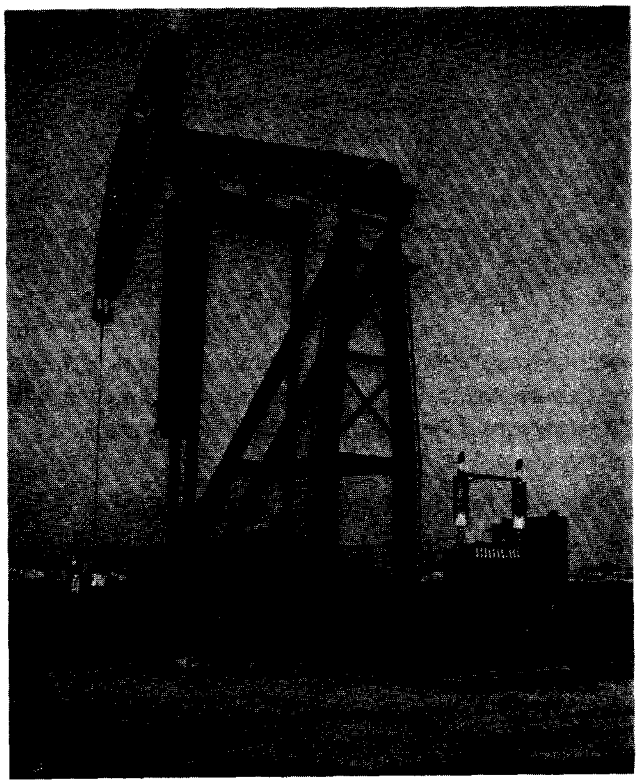

FIGURE 4

The World's largest sucker rod pumping unit, 240 in. stroke air balance unit with a 2,550,-000 in.lb. speed reducer and a 47,000 lb. structure.

space and maximum compression ratios in the pump chamber. Some of the advantages of this new pump are the reduction or elimination of pounding, improved volumetric efficiency, decreased rod load range and in some cases, increased production.

This pump is particularly adaptable to heavy crude wells because of the large unrestricted inflow areas. It is also desirable for steam flood wells for it has a two-stage effect and the components of the pump are designed to operate under high temperatures (up to 500°F). The new pump is also adaptable to high gas/oil ratio wells because of the close spacing of the valves and the two-stage effect provided by the ring valve, and to waterflooding and sandy wells.

ENERGY LOSSES

Since every type of artificial lift system — rod or rodless — has certain similar energy losses in elevating the fluid from the bottom-hole pump to the surface, only those losses between the surface equipment and the bottom-hole pump are considered here. The average loss in transmitting power from the polished rod to the bottom-hole pump in a sucker rod system is quite modest — usually running no more than 15 to 20 per cent. These energy losses, when referred to a basis of loss per thousand feet of depth, are reasonable and possibly lower than any other type of artificial lift system. With the exception of normal friction loss, a foot-pound of work performed at the polished rod is transmitted to the bottom-hole pump with extremely high efficiency, for there is no way for the rods to dissipate the entrained energy except by friction.

MAXIMUM PRODUCTIVE CAPACITY

Taking advantage of the various improvements in sucker rod pumping unit technology, it is currently possible to lift 9000-10,000 BFPD from shallow to medium depths, safely and economically with the largest sucker rod pumping unit. This is approximately twice the fluid volume currently handled by existing sucker rod pumping systems.

As an example, suppose a 240-in. stroke sucker rod unit were pumping approximately 11 SPM (maximum pumping speed based on 70 per cent free rod fall) and driving a 5-3/4 in. pump — the production at 100 per cent volumetric efficiency would exceed 9500 BPD. This volume could be lifted from depths as great as 2-3000 ft.

The curves in Figs. 5 and 6 show the typical maximum productive capacity of a sucker rod system vs. depth for two large units. 100 per cent volumetric efficiency is assumed.

FIELD STUDIES

Using the new computerized analytical technique, some 1000 sucker-rod-produced wells have been carefully analyzed and the results obtained (Table IV). It is important to recognize that these wells were not necessarily chosen for their high productive capacity; they were surveyed at random from wells of approximately 100 different operators to study the producing characteristics of each well. The wells are grouped in three categories: (1) 0-2500 ft., (2) 2500-5000 ft., and (3) deeper than 5000 ft. It should be re-emphasized that these wells are not necessarily maximum fluid producers — but a representative cross-sectional sampling of producing wells both domestic and abroad.

CONCLUSIONS

By taking advantage of the increased size and capacity of the various component parts of a sucker rod system, it is possible to lift tremendous volumes of fluid with maximum reliability, effectiveness, and economy.

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3. Various Engineering Data—USI Manufacturing Co., Longview, Texas.

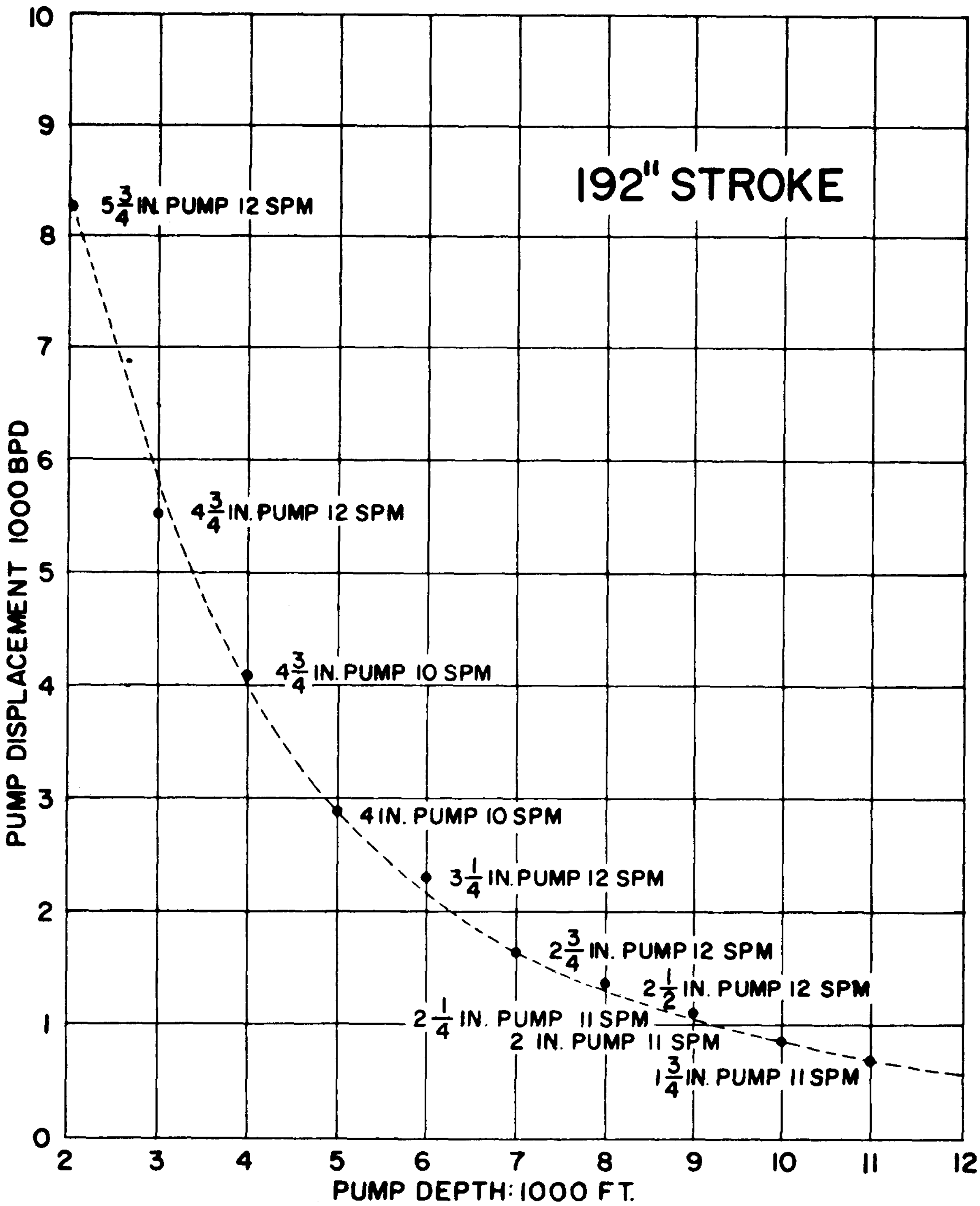

FIGURE 5

Maximum Pump Displacement vs. Depth, A-1824-192-47 Pumping Unit. (Assumed Pump Submergence 500 ft, S.G. 0.9)

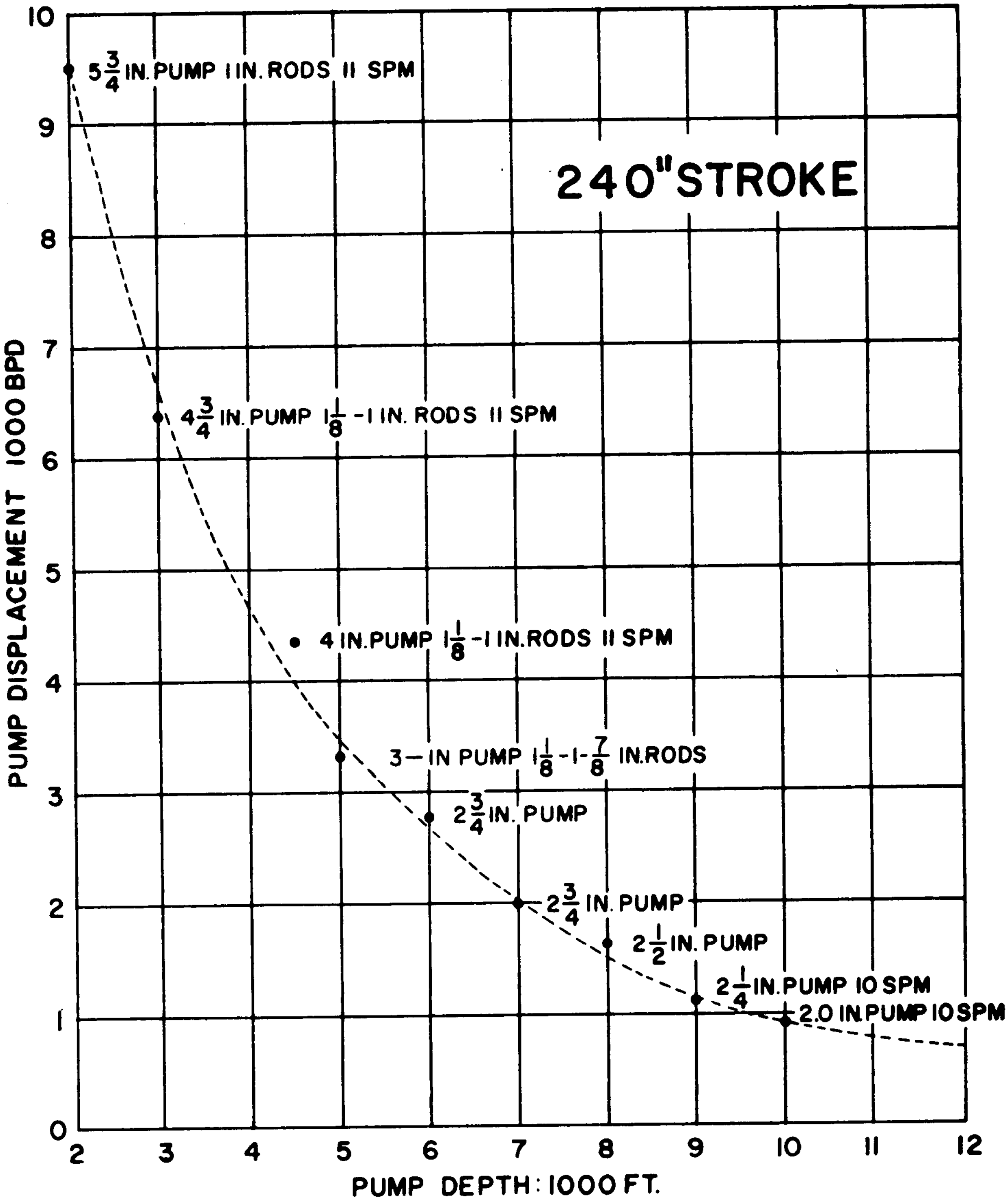

FIGURE 6

Maximum Pump Displacement vs. Depth, A-1824-240-47 Pumping Unit. (Assumed Pump Submergence 500 ft, S.G. 0.90)

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TABLE IV

Unit Type Size	Pump Cycle SPM x Lgth.	Depth	Prod. Test BFPD	Rods*	Plunger	Max. Load	Min. Load	Range % Max.	Max. Stress	Computed PRHP	Power PHP/ PRHP
Well Depth — 0-2500 Ft. Production — Over 2,000 BPD											
168-G912-DL	10.7 x 134	2498	2317	87	3.75	12,496	4,085	67.3	15,900	20.5	.698
T36F-120-365-D	10.0 x 120	1367	2064	77	3.75	11,295	1,183	89.5	18,800	22.0	.763
Well Depth — 0 to 2,500 Ft. Production — Over 3,000 BPD											
A912-120-36	15.7 x 120	2026	3455	86	3.75	8,004	2,821	64.8	10,250	9.8	-**
A912-120-36	15.3 x 120	2022	3390	86	3.75	5,832	1,275	78.1	7,430	5.6	-**
Well Depth — 2500 to 5000 Ft. Production — Over 1000 BFPD											
A128OD-192-42	9.3 x 192	3997	1120	98	2.75	25,216	5,372	78.7	25,400	61.0	.781
A128OD-192-42	9.2 x 192	4016	1084	98	2.75	24,010	5,932	76.3	25,200	54.3	.743
A128OD-192-42	9.2 x 192	3979	1040	98	2.75	28,190	5,922	79.0	28,350	59.3	.778
**Well not pumped down.											
Well Depth — 2500 to 5000 Ft. Production — Over 1200 BFPD											
A912-192-40	10.0 x 192	3208	1493	86	2.75	20,607	2,995	85.5	26,300	44.2	.782
A912D-120-56	13.3 x 120	4041	1374	87	2.75	23,597	1,847	92.2	30,000	40.2	.765
A640D-120-36	11.7 x 120	4410	1300	97	3.25	31,121	5,776	81.4	31,300	43.0	.815
Well Depth — 2500 to 5000 Ft. Production — Over 1500 BFPD											
A912DB-144-40	9.2 x 144	3222	1739	87	3.75	20,854	3,054	85.4	26,600	33.72	.808
144-640DL-30BS	14.8 x 144	3525	1640	87	2.75	17,520	4,460	74.5	22,300	30.3	.541
ABH-912-40	9.2 x 192	2582	1635	87	3.25	18,222	2,888	84.2	23,200	39.9	.725
Well Depth — 2500 to 5000 Ft. Production — Over 2000 BFPD											
168-G912	11.3 x 168	2505	3775	87	3.75	24,164	2,482	79.6	15,500	23.4	.410†
168-G912-32	11.3 x 168	2521	2709	87	3.75	12,086	2,338	80.1	15,400	22.2	.695
M640D-305-168	8.0 x 168	2993	2110	87	3.75	24,164	1,844	92.4	30,700	45.3	.832
†Worn pump.											
Well Depth — Over 5000 Ft. Production — Over 800 BFPD											
C912D-356-144	15.8 x 106	5548	884	97	2.50	32,505	4138	87.2	33,700	49.3	.723
C640D-144-304	11.2 x 144	5240	846	86	2.25	22,992	4180	81.9	29,300	34.4	.772
30DA-320F	17.8 x 86	5028	814	76	2.75	22,715	3595	79.8	37,800	36.8	.829
Well Depth — Over 5000 Ft. Production — Over 900 BFPD											
A1824D-240-47	6.3 x 240	6043	974	87	2.75	30,931	6093	80.4	39,400	56.6	.686
M912D-305-168	11.8 x 168	5474	967	86	2.25	26,536	1123	95.8	33,800	50.7	.726
A640D-120-36	16.3 x 120	6902	908	86	2.00	30,355	3629	88.0	38,700	57.2	.729
Well Depth — Over 5000 Ft. Production — Over 1000 BFPD											
M640D-253-144	10.2 x 128	6160	1588	76	2.75	23,403	5888	74.9	39,000	32.3	.827
A1280D-216-41	9.2 x 216	8500	1054	86	2.75	32,906	7855	76.2	41,900	54.3	.758
M912D-305-168	11.1 x 168	5475	1022	86	2.50	26,804	2711	89.9	34,200	51.5	.755

*API rod No. shown refers to the largest and smallest rod size in eighths of an inch. For example, 76 is a two-way taper of 7/8 and 6/8 rods; 97 is a three-way taper of 9/8, 8/8 and 7/8 rods.