

Beam Pumping System for Deep High Volume Wells

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Abstract

Worldwide there are over 949,550 producing oil wells, about 93 % of these wells are operated using different artificial lift methods and roughly over 72 % are producing using beam pumping system.

In the past, the ability of beam pumping systems to produce high volumes from deep wells was limited due to two main reasons: (1) the high rod and fluid loads, and (2) the lack of deep understanding of the behavior of complex sucker rod system and the involved nature of the reservoir with its contained fluids and inflow performance.

Nowadays, the existence of the following elements led to producing high volumes of production from deep wells: (1) development of relatively long stroke enhanced geometry pumping units with good quality high tensile strength sucker rods and more accurate predictive software, (2) accurate on site monitoring and control tools, and (3) pumping using large plungers with high pumping speeds.

This study was undertaken using advanced predictive methods, high strength rods, optimum pumping mode, and unit geometry to design Beam pumping system for deep and high volumes oil wells. Three geometries of different surface pumping units were analyzed and studied including, conventional, Reverse Mark and Mark II units. Each geometry of these three types has been subjected to different design features that affect torque and different linkages affecting its kinematics behavior. The highest strength sucker rod string, beam unit geometry, stroke length, pumping speed and subsurface pump size were varied and analyzed jointly to obtain optimum pumping parameters capable to produce maximum fluid at different well depths. This study considered and applied many variables including; well depths from 1,000 to 15,000 ft, water cuts from 0.0 to 100 %, different pump sizes from 1.25 to 5.75 in, stroke lengths from 100 to 260-inch, and non-API high tensile sucker rods.

The results indicated that the lifted liquid volumes and pump seating depths for deep wells can be effectively increased using the beam pumping systems. The surface unit geometry has shown a crucial effect of increasing the produced quantity from deep wells. The study recommended using conventional pump unit for shallow depths. The enhanced geometry pumping units of Mark II and reverse Mark have been proven the superior type for deep high volumes wells because it required the least torque to lift the same quantity from different well depths. The study also presented successful field applications for deep wells producing high volumes.

1. Introduction and Review

Downhole pumps are a common means for enhancing the productivity of a well by reducing the bottom hole pressure. Two types of pumps are used including positive-displacement pumps (which include sucker rod pumps and hydraulic piston pumps) and dynamic displacement pumps (Economides et al, 1993).

Beam pumping system is the first and may be the last artificial lift system. A century ago the most universal mechanism for artificially lifting fluid was the standard Shadoof. The earliest documented walking beam and sucker rod pumping system is described in Egyptian historical writing dated 476 AD², as shown in **Figure 1**.

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One century ago, the system mechanism was upgraded for artificially lifting fluid in an oil well to a standard rigfront. It was a wooden walking beam driving a string of hickory sucker rods, often called “well poles” as many as ten strokes/minutes and 15-in stroke length with the maximum tensile stress of the rods about 12,800 psi. The bottom hole pump was cast iron or brass with the barrel approximately 1.5-in in diameter and well depth ranged from 500 to 1,000 ft. The torque capacity of the band wheel and flat-belt speed reducer ran only a few thousand inch-pounds, and the unit’s structural capacity was from 1,000 to 1,500 lb³.

The ability of a sucker rod pumping system to produce a fluid is constrained by (1) the stroke length, (2) the rod free fall from a given well, (3) the plunger diameter of the bottom-hole pump, (4) the strength of the sucker rods, and (5) unit geometry. For any given unit geometry, critical pump speed is controlled by two variables, (1) stroke length, and (2) the well forces, such as friction, buoyancy, etc., that retard rod fall (Byrd, 1968).

Byrd (1968) reviewed some field studies to conclude the practicality of high volume production with sucker rods. He reported that the new development in pumping units with 240-in maximum stroke had structural capacity exceeds 47,000 lb, with a torque rating greater than 2.5 million in-lb, which is capable to produce quiet high volumes from relatively deep wells. He also indicated that practical sucker rod pumping approaches 13,000 ft, and capacities of producing 5,000 and 6,000 B/D from shallow to medium depths easily. In addition, volumes of 9,500 B/D were considered practical with sucker rod pumping equipment at that time. The study did not cover the rod buckling tendency, as it will be covered in this study.

In the present, the structure and geometry of a modern pumping unit reaches 260-in maximum stroke with structural capacity exceeds 47,000 lb, and the torque rating greater than 2.5 million in lb. The plunger diameter for some bottom-hole pumps (casing type) runs as high as 5.25 in or bigger size can be built based on the manufacturing capacity. Sucker rod strength, it

might be the greatest improvement in the sucker rod, which may have a tensile stress of some 150,000 lb.

2. Modern Beam Pumping System

The comparison of the modern sucker rod system with its counterpart of 100 years ago reflects some startling figures. The structure capacity of the modern surface units has increased nearly fifty-fold; the torque capacity perhaps a thousand fold; the area of the bottom-hole pump over 20 times; the stroke length nearly twenty-fold; and maximum rod tensile stress nearly 12 times. With the increased stroke length, rating torque and structure capacity, relatively high volume can be produced from quite deep wells.

3. Surface Pumping Units

3.1. Conventional Pumping Unit

The conventional pumping unit is a modern version of the crank counterbalanced unit first built in 1926. It is a rear mounted Class I lever system. The equalizer bearing is directly in line with the gear reducer slow speed shaft. This machine is bi-directional, meaning it can be rotated both clockwise and counterclockwise with approximately the same performance characteristics in either direction as shown in **Figure 2**.

The API geometry dimensions set the kinematics of the machine and thus its performance. The conventional geometry works best with a dynamometer card that slants upward on the right end (above). This type card is called an under travel card. The geometry will work on all shapes of dynamometer cards but will turn the under travel card into the lowest peak torque.

3.2. Mark II Pumping Unit

Mark II pumping, as shown in **Figure 3**, has shown features that differentiate it from other pumping units, as follows;

1. The gear reducer slow speed shaft is located at the rear of the equalizer bearing such that the crank turns 195 degrees of crank rotation for the up stroke and 165 degrees of crank rotation to complete the down stroke.
2. The walking beam pivots from the rear end and the pitman pushes up on the walking beam to lift the load (class III lever).
3. Unidirectional unit must turn counterclockwise only, and
4. The crank is offset, which causes the counterbalance torque to better align with the well torque.

Acting together, these features create a more uniform torque that usually creates less peak torque than a conventional unit for a given set of well conditions. It normally requires less motor horsepower and uses less energy than a conventional unit doing the same work.

This machine favours an over travel dynamometer card (above) but can work with all shapes of cards. This will turn the load of a card that slopes downward on the right end into the lowest value of peak torque.

3.3. Reverse Mark (RM) Pumping Unit

This unit uses some features of the Mark II type applied to the conventional geometry. It has a phase angle in the cranks that creates an up stroke of 190 degrees of crank rotation and has phased counterbalance, as shown in **Figure 4**. This unit is unidirectional and must turn in a clockwise rotation only. It is important to note the offset of the gear reducer relative to the equalizer and the crank pin angular offset similar to the Mark II

This geometry usually produces less peak torque than a conventional unit for a given set of well conditions and normally requires less motor horsepower and uses less energy to do a required job. This geometry likes a flat dynamometer card (above) that has the peak load occurring about mid up-stroke and minimum load occurring about mid down-stroke. It will work with all shapes of cards but prefers the flat card shape where it does the best job of turning well load into lowest torque.

Cases Histories

Clegg (1988) presented the production capabilities of the rod pumping system for various lift depths from 1000 to 10,000 ft, **Figure 5**. He made the design based on the largest beam pumping unit manufactured at that time which was conventional type of size C-912D-365-168.

As also shown in **Figure 5**, Takacs (2003) modified Clegg work (1988) by adding data given by Byrd (1968) plotted on the same figure representing Mark II types of pumping units and may be regarded as the ultimate production capacity of present-day sucker-rod pumping installations. It is clearly visible from the above pumping capacity values that attainable rates progressively decrease with increasing lifting depths. This is logic, because when high volumes are lifted from deep wells, the main limitation of sucker-rod pumping chain is the strength of the rod string. For high-volume shallow wells, this is not a problem since rod strength is not usually exceeded by rod stresses. For that type of wells, the main concerns are normally the fall of the rod string during down stroke and torque rating of the gear reducer.

Well 41X24D of the Reno field in Wyoming's Powder River basin became the world's deepest rod pumped oil well on Sept. 21, 1982. Before this installation, the maximum depth experience was limited to about 11,500 ft [3505 m]. Its rod pump, installed at 14,500 ft [4420 m], has operated successfully since 1983, as reported by Gott (1983).

Gott's study (1983) indicated that this rod-lift system replaced a hydraulic lift installation use since the completion of the well in 1966. Poor hydraulic pump operating economics coupled with frequent pump servicing and associated downtime dictated change. Records maintained by the production foreman revealed that well 41X24D had logged 14 hydraulic pump failures during the previous 12 months of operation. Cost of these failures approached \$25,000. During an annual well review, a recommendation was made to convert the well to rod lift to improve the situation. He also indicated that after well 41X24D operated successfully for 14 months, Reno 43X19A was converted from hydraulic lift to beam lift on Nov. 18, 1983. Equipment design for Reno 43X19A differed slightly from the previous conversion.

A Mark II 640-365-144 pumping unit was installed, along with a Size 4 ultra-high-slip motor (24 to 51 hp [18 to 38 kW]), and the pump was set at 14,863 ft [4530 m]. Production before the conversion was 65 BOPD [10.3 m³] and 0 BWPD water. Production increased after conversion to 98 BOPD [15.6 m³] and 0 BWPD water. No failures were experienced on this well before July 1985 (Gott, 1983). On July 1, 1985, Shell's Wyoming D/J Unit, including the

Reno field wells, was sold. Information contained in this paper pertains only to Shell's operation of the wells before the date of sale.(Gott, 1983)

Another history case was presented in an Oklahoma operator reported lifting 1,147 B/D from 8,025 ft., pumping 8.75- 216" SPM with a 24" plunger, and an API-96 rod string. Peak polished rod load measured 37,052l bs; the minimum polished rod load 7,080 lbs.; while the in-balance peak torque measured 874,000in.lbs.on an API 1,280,000in.lbs.gear reducer (Gott, 1983).

Practical experience through 1970 in Getty Oil Company's C-Block Waterflood indicated a realistic peak production capability of approximately 500 B/D from rod pumping equipment. The peak production was achieved by use of a 2" bore pump in combination with a 1,280,000 in.-lb. pumping unit gear reducer. Field experience demonstrated the limiting factor to be sucker rod strength. Application of the ultra-high strength sucker rod has increased the production limit to approximately 1000 B/D; the higher production rate requires use of a 2-3/4" bore pump, ultra-high strength API size 86, and a 1,824,000 in-lb pumping unit gear reducer (Ditmore, 1973)

4. System Design Considerations

The typical sucker rod system design involves using a predictive computer program (API or wave equation) to generate possible solutions for sizing the surface and subsurface equipment. Based on the field and engineering experiences, if the production predicted by the program is acceptable, without exceeding the equipment limitations and rod running without buckling, then the design is completed.

This study was made using SROD software (Lufkin) to determine the system capabilities to produce maximum practical fluid from different depths, 1000 ft to 15,000 ft. Since sucker rod strength is the limiting factor in high volume beam pumping, the highest strength sucker rod string is considered in addition to the API grads. The beam unit geometry, stroke length, pumping speed and subsurface pump size were analyzed jointly to obtain optimum pumping parameters to produce maximum fluid at different depths of the well. **Table 1** presented the criteria used in the design.

Table 1. Criteria used in the design.

Depth	From 1000 to 15,000 ft
Rod grad	C, D and N97
Pumping intake pressure	200 psi
Well head pressure	150 psi
Oil API	40
Gas/oil ratio	0-3000 scf/stb
Water cut	0 – 100 %
Subsurface pump size	1.25-5.75 inch (for the larger plungers, the application may require the use of on-off tools)
Pumping units	Lufkin conventional, Mark-II and reverse mark
Pumping speed	5-20 SPM
Stroke length	100-260 Inch
Sucker rod	All API grads plus N97 with 0.9 service

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A number of general assumptions were applied in making these calculations.

1. In all cases the tubing was considered anchored, thus no tubing stretch.
2. Casing can accommodate the required tubing size

The system was designed for three different cases as follows:

1. All the produced fluid was water with fluid gradient 0.433 psi/ft
2. The system produced fluid with 50% water cut where gas/liquid ratio (GLR) is zero
3. The system produced fluid with 100% oil and Gas/oil ratio (GOR) is zero.

Three different surface pumping units geometries were studied including, conventional, Reverse Mark and Mark II units. Each of these three geometry units has different design features that affect torque and different linkages that affect its kinematics behavior. Because each well is different, one of these unit types may out perform in comparison to the others for a given set of well data and for the end user's design goals. When designing a Beam Pump installation, different geometries were considered to determine the best performance for the intended result.

5. Result and Discussion

The results of production versus pump seating depth for conventional, Mark II, and reverse Mark are shown in **Figures 6, 7, and 8** respectively, for three water cuts of 0.0, 50 % and 100 %.

Figure 9 compares the capacity of the three different geometries and indicates that at shallow well depths of 1,000 and 2,000 ft, the conventional unit produces higher production than or at least comparable to the other two types. This recommendation is also valid up to 4,000 ft well depth. However, at deep well depths greater than 8,000 ft, the production from the three types is very comparable. The attained axial load versus well depth is depicted in **Figure 10**.

As shown by these four figures, Figure 6 to Figure 9, and as might be expected, in general, in high production rate, shallow wells, the conventional pumping geometry works good and it can handle up to more than 8200 BFPD with the subsurface pump seated at 1000 ft depth and dynamic fluid level about 500 ft from surface. This value of production is not the end limit of the equipment, unit, rod and tubing all can handle more volume. For example in order to produce 8,200 BFPD the calculated required torque was 1,190,000 in-Ib and the peak polished rod load was 20,346 Ib. Then still there is a room for more torque and structure load In comparison with the current present units which can handle up to 1,820,000 in-Ib and 47,000 peak load.

Consider the rod string condition, the rod string was grade D loaded with 80 % of its maximum load. Even the rod still can lift more loads, where still 20 % room in that grad and more than 50 % for the ultra high strength rods. The size of the subsurface pump was 5.75". All those numbers show that there is no problem of the equipment to handle more volume.

The rod fall is considered as one of the major problems and normally occurring. **Figure 10** shows the limit of the pumping speed reached to design the previously-mentioned well. The existence of any more friction in the pumping speed will result in a negative polished rod load. Therefore for shallow well high volume, larger rod size is used for the purpose of increasing the minimum polished rod load. Consequently positive down stroke load and rod can fall free. The reason is to avoid negative minimum load, Slack will be thrown in bridle. It has been recognized that increasing the pumping speed is restricted by the downward velocity of the horse-head during the down-stroke. As the pumping speed increases the Carrier bar begins to move faster on

the down-stroke than the polished rod (especially for enhanced geometry pumping types), which falls due to total rod weight acting on it. At the beginning of the upstroke, the carrier bar is moving upwards at the same time the rod is still moving downward, resulting in carrier bar hitting on the polished rod clamp. The high impact forces can create large torques which can easily overload the pumping unit structure and damage the gear reducer tooth. The pumping speed at which this phenomenon starts to occur is called the critical pumping speed (Lufkin). This is affected by retarding forces such as friction (in the stuffing box, rod-to-tubing, fluid, etc.) and buoyancy (Lufkin). Surface stroke length has a direct impact on critical pumping speed; the longer the stroke, the lower the maximum pumping speeds that can be allowed.

Lufkin proposes the following equations:

For conventional geometry

$$SPM = 0.7 \sqrt{\frac{60000}{L}} \quad (1)$$

For enhanced geometry

$$SPM = 0.56 \sqrt{\frac{60000}{L}} \quad (2)$$

For deep well, high tensile rod string is used in the design. For that high tensile rod string, it is extremely important to design rod string taking into consideration rod handling. If there is any corrosion environment expected, an effective chemical treatment is recommended. However currently in the market, there is a quite high quality sucker rod which can withstand corrosion for a certain limit such as grade KD 90.

Many studies in the literatures (Derek et al., 1988; Pope, 1993) and field practices (Nolen, 1969; Wan, 1986, Murtha et al, 1987), concluded that the enhanced geometry pumping systems has been proven to be an economically feasible type when the unit is capable to lift fluid from medium to deep wells (+6000 ft) and this type geometry features create a more uniform torque (usually create less peak torque for a given set of well conditions than a conventional unit

The design shows that fluid lifting capacity of a rod pumping system is limited by several factors. The main limiting factors are: (1) the pumping speed, (2) the strength of the rod material, (3) the structural capacity of the pumping unit, and (4) rod buckling

The system design accounts for all effects using various pumping parameters having impact on pumping rate and included in the design of the rod string as well. At this point the rod string is designed by setting the rod stresses equal at the top of each taper section for high-strength rod materials. These parameters are checked against the limiting factors: (1) Peak polished rod load versus the unit's allowable structural load, (2) Peak net torque vs. the speed reducer's torque rating, (3) Pumping speed is compared to its critical value by checking the calculated minimum polished rod load. Obviously, critical pumping speed is detected when minimum polished rod load approaches zero as a result of the carrier bar leaving the polished rod clamp, and (4) Rod buckling, Sinker bar is considered for rod string shown tendency of buckling.

5.1. Effect of Surface Unit Geometry

The design output match with all published literatures (Allen, 1969; Gibbs, 1977; Murtha et al., 1987; Derek et al. , 1988; Pope, 1993) and field practices (Nolen, 1969; Wan, 1986, Murtha et al, 1987), where all agreed that the enhance geometry pumping systems proved to be the

economical type of pumping units lifting fluid from medium to deep wells. Where geometry features of that type create a more uniform torque and thus usually create less peak torque for a given set of well conditions than a conventional unit. It normally requires less motor horsepower and uses less energy than a conventional unit doing the same work. **Figures 11, 12 and 13** present a comparison of required torque, peak polished rod load, and required motor power of the three above-mentioned pumping unit's geometries for different well depths, respectively. The comparison was based on attaining fixed target production at three different depths, of 200, 700 and 1,500 BFPD at 5,000, 10,000 and 15,000 ft depth, respectively.

As shown in **Figure 11**, the MII pumping unit is the superior unit as the least required torque to lift the same quantity from the different depths while the conventional one showed poor performance. This is because, the front mounted Class III lever system geometry of that unit insure optimum torque carrying capacity. The reverse mark geometry lies in the middle between the Mark and the conventional type. With respect to the load as shown in **Figure 12**, it is shown that up to about 8,000 ft the reverse Mark geometry require the lowest load to lift the same quantities of fluids. More than 8,000 ft and up to about 13,000 ft MII will require less but not far than the RM geometry and still the conventional far than the two geometries. All those reflect in the required motor power as shown by **Figure 13**.

Conclusions

This simulation study was achieved using actual field data. It analyzed and studied the performance of conventional, Reverse Mark and Mark II pumping units under different well conditions and variable pump characteristics. The following conclusions can be drawn as follows:

1. The depth from which beam pumping system effectively lift fluid can significantly be increased by using high strength rods, optimum pumping running parameters and enhanced unit geometry.
2. The problems of lifting high rates from shallow wells are quite different than that of lifting from deep wells. Therefore, the use of modern equipment and operating practices allow fairly large volumes to be pumped,
3. The conventional pumping unit is recommended for shallow well depths up to 2,000 ft because it provides the highest quantity under the same operating conditions of Mark II and Reserve Mark pumping units.
4. The Reverse Mark pumping unit has provided the superior lifted quantity than other types of Mark II and conventional ones because it required the least torque to lift the same quantity from different well depths up to 8,000 ft. for greater depths , Mark II units is recommended. However well conditions can play some other rules between choosing Mark II and Reverse mark Units at those depths.
5. Historical cases have proven successful application of producing high volumes from deep wells using different bean pumping systems.

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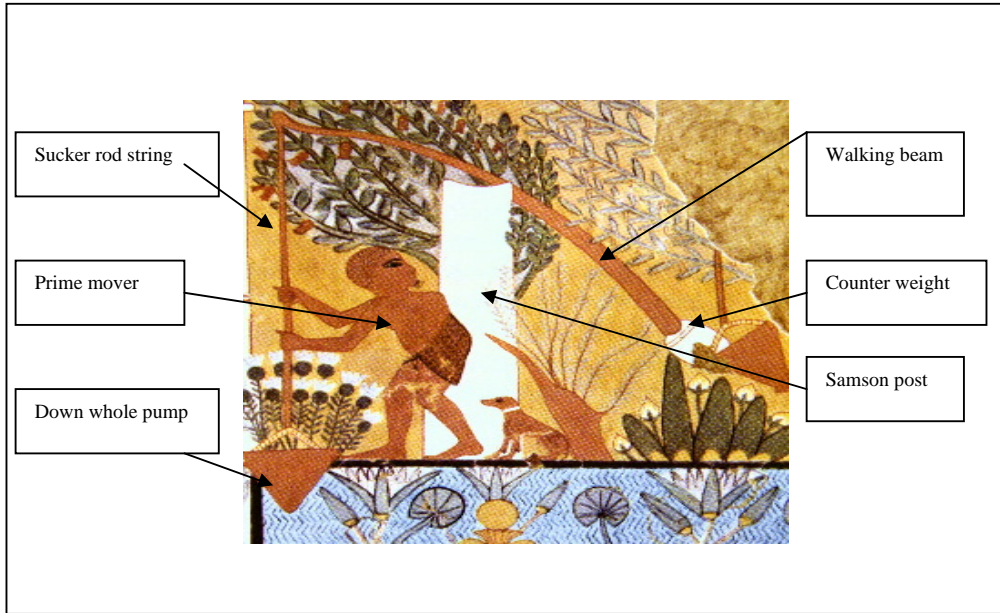


Figure 1. Typical Egyptian beam system running with beam balance pumping unit type.

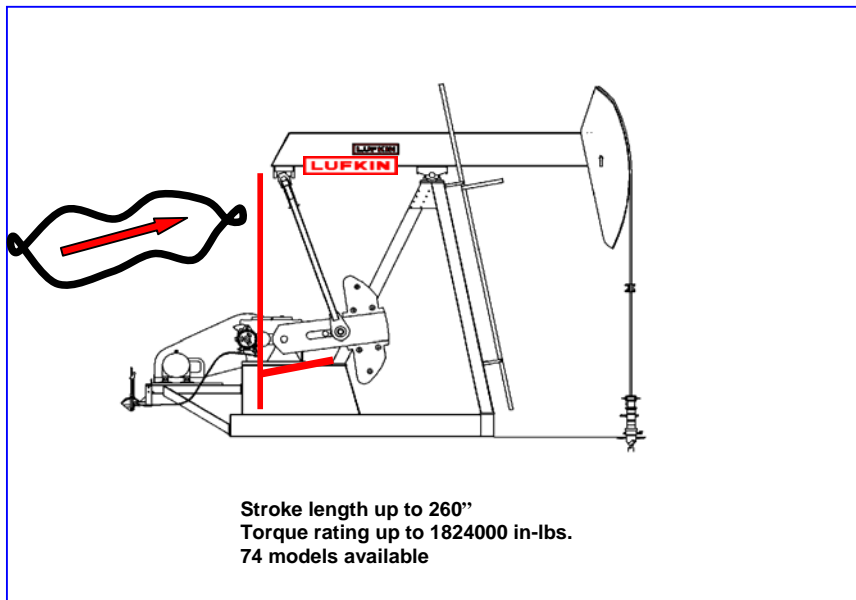


Figure 2. Conventional pumping unit

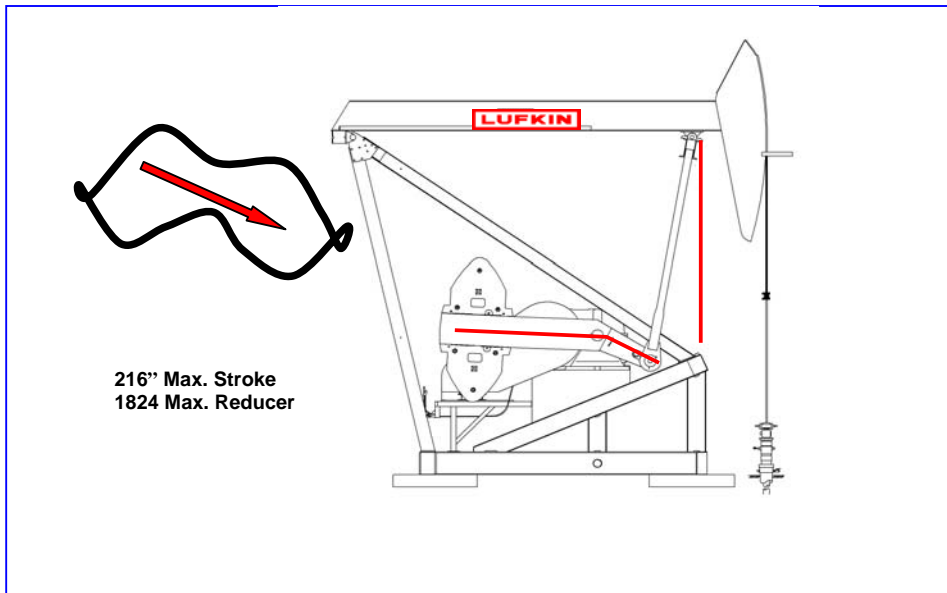


Figure 3. Mark II pumping unit

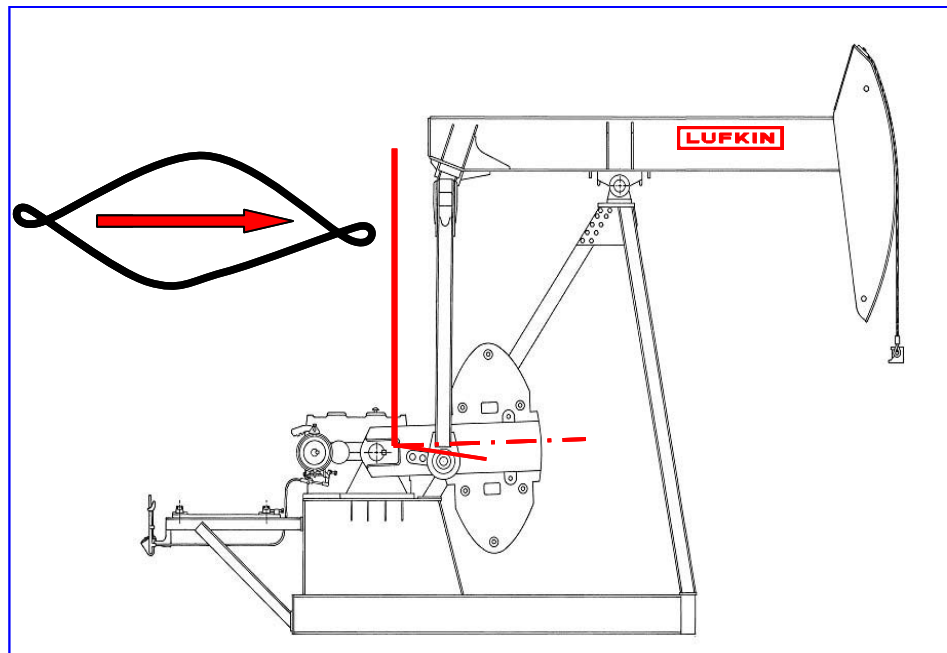


Figure 4. Reverse mark pumping unit

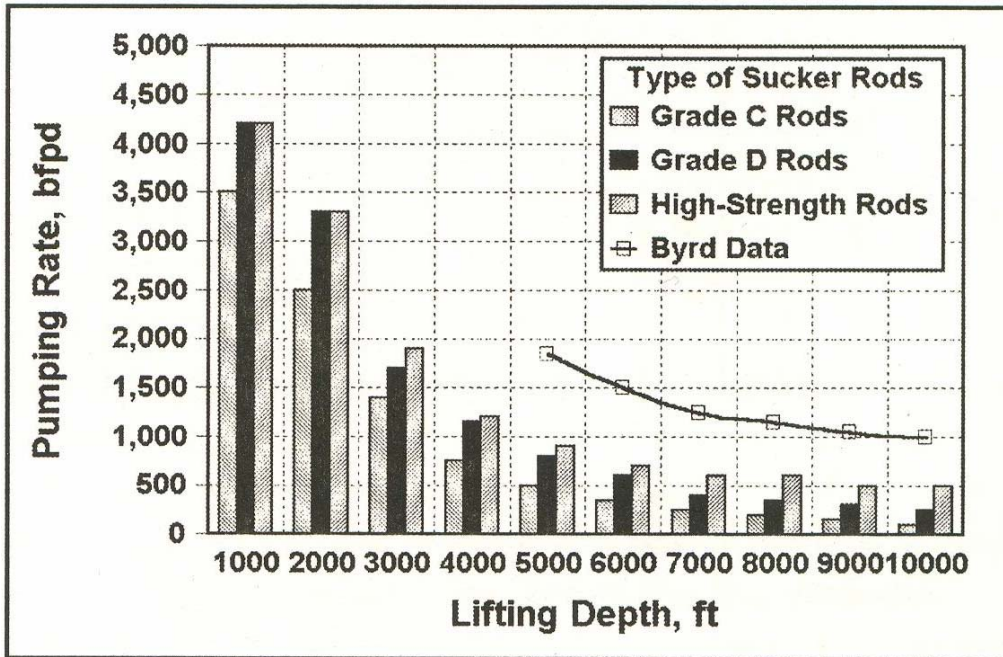


Figure 5. The approximate maximum rates for conventional pumping units (after G. Takacs¹)

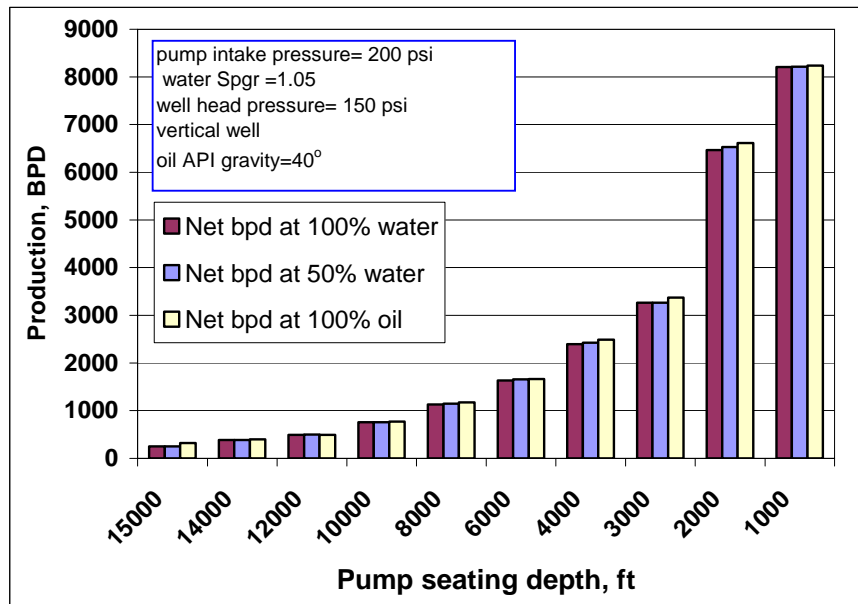


Figure 6. Production versus Depth for conventional Pumping Unit.

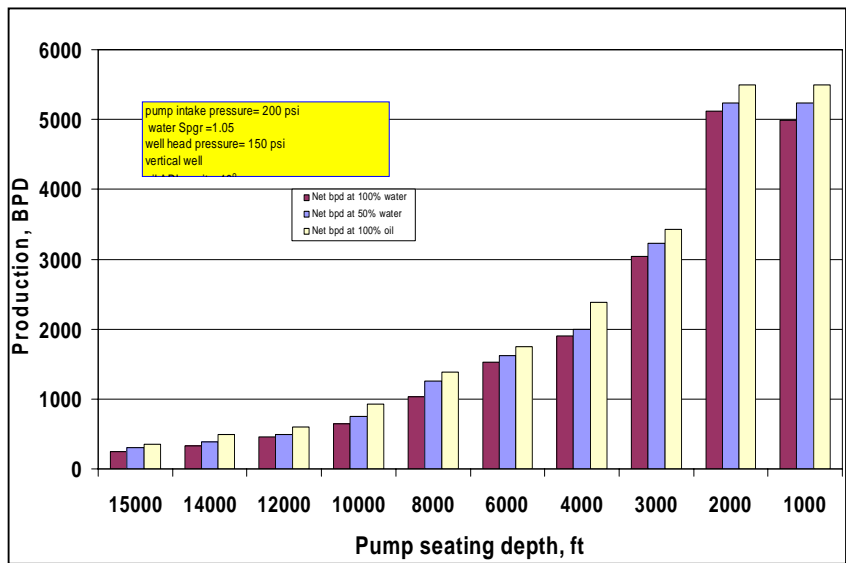


Figure 7. The pumping capacity for Mark II pumping unit.

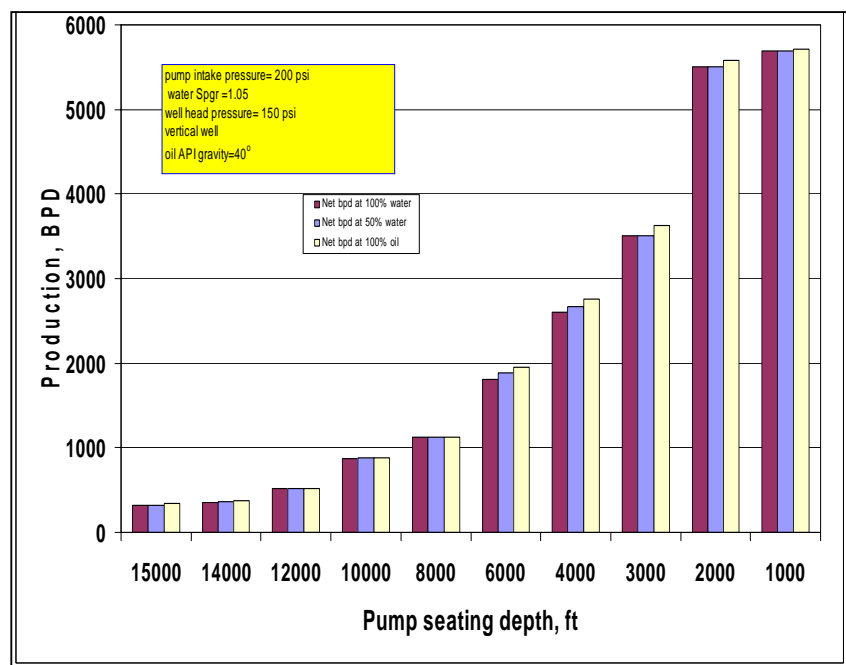


Figure 8. The pumping capacity for RM pumping unit.

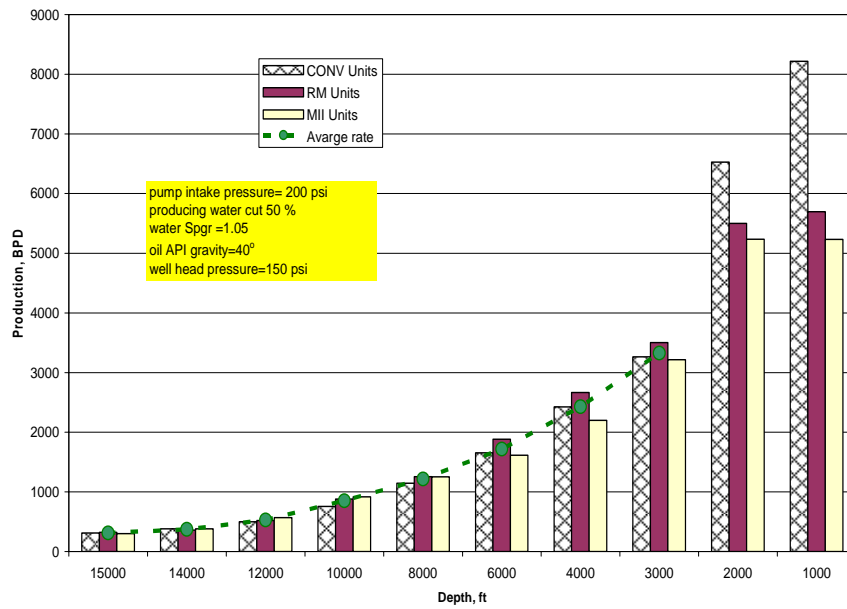


Figure 9. Comparison the capacities of the three different geometries.

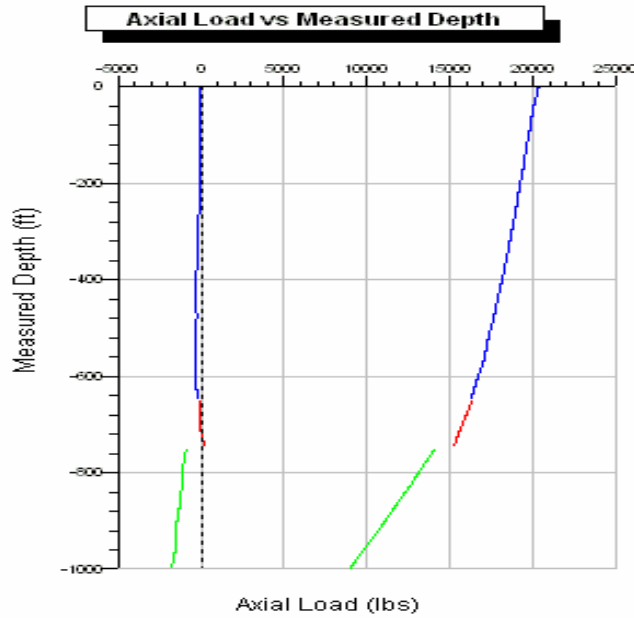


Figure 10. Shows the axial load versus depth.

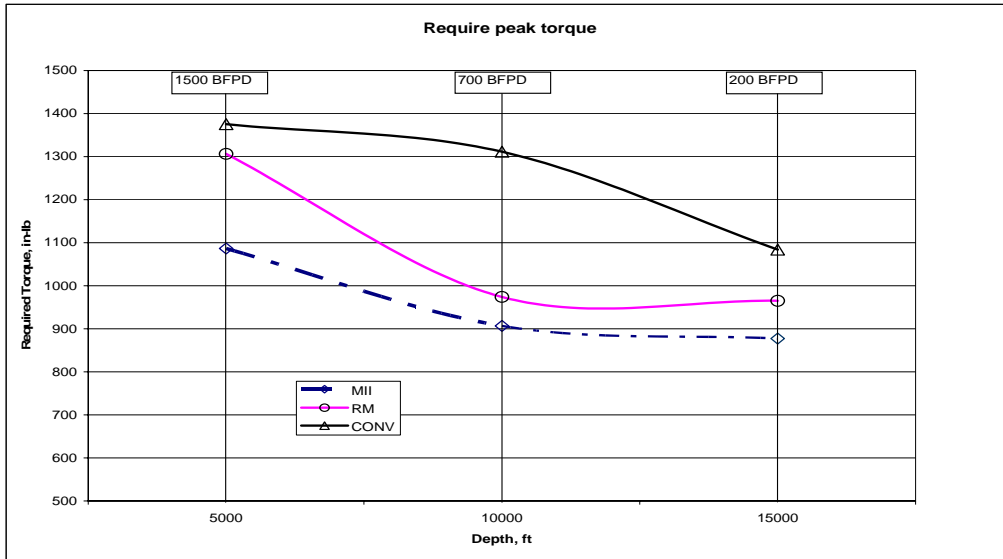


Figure 11 – Required peak torque versus depth.

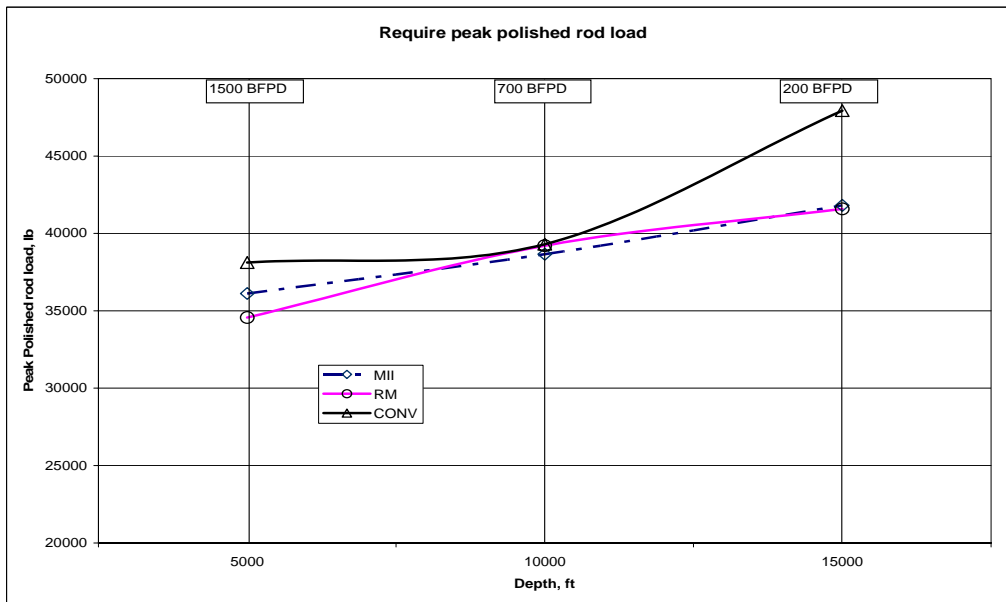


Figure 12. Required peak polished rod load versus depth.

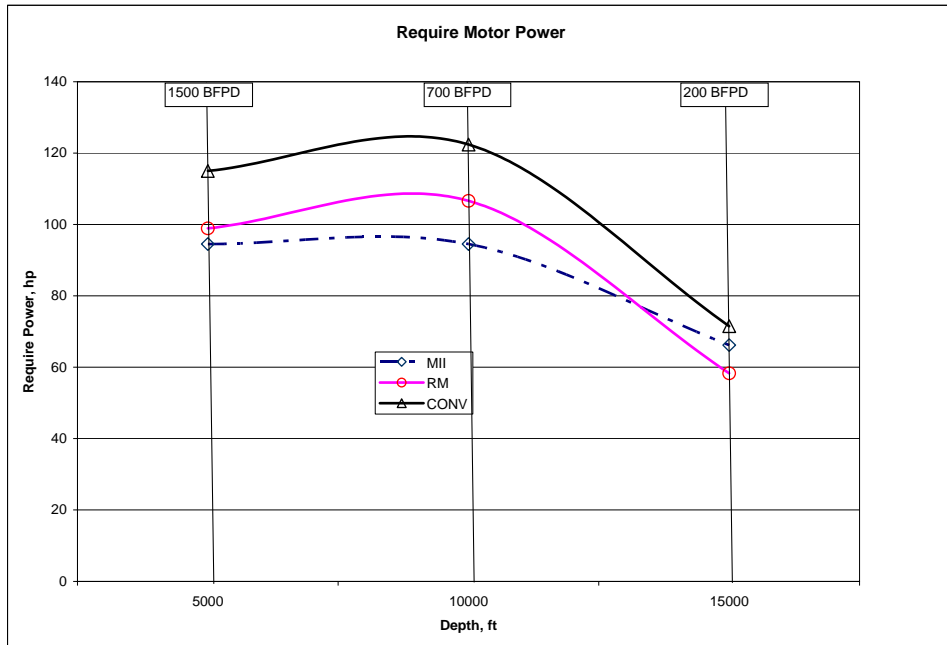


Figure 13. Required motor power versus depth.