A FASTER DOWNSTROKE IN A BEAM AND SUCKER ROD PUMPING UNIT -- IS IT GOOD OR BAD?

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ABSTRACT

A faster downstroke in a beam and sucker rod pumping system, traditionally considered unfavorable to the best production practices, may have some surprising, beneficial side effects not readily apparent to the casual observer. This particular kinematic characteristic may increase productivity in several ways; reduce peak rod and structural load and maximum rod stress; deliver more safe work to the bottomhole pump; and in some cases even decrease rod load range and soften the impact resulting from fluid and gas pound. The following discussion illuminates some aspects of this often misunderstood characteristic of reverse geometry units like the air balance and Mark II.

INTRODUCTION

Many oilfield production personnel are familiar with the possibility of a beam and sucker rod pumping unit being driven so fast that, during the downstroke, the hanger may run away from the falling rods. Does this occur often, and is it a threat to good field practice and maximum production? If it is, are there any desirable, offsetting, considerations? If so, what are they? It is almost intuitive to suppose that a faster downstroke is damaging to the rods; that it stacks, or drives them into harmful compression. What about fluid or gas pound? Wouldn't a faster downstroke punish system components more severely? Certainly, maximum production is a function of pumping speed. Does this mean that the unit pumping the greatest number of strokes per minute, on a particular well, produces the most fluid? When considering these basic questions, often misconceptions arise. The following discussion attempts to clear up some of the misunderstandings, and develop a better perspective of these important concepts.

GENERAL

Momentarily disregarding harmonic forces in the rod string, and assuming the unit is pumping all the fluid available at the well bore - for a given SPM (assuming constant angular velocity at the crankshaft as a reference), three factors normally control downstroke rod motion and, in turn, maximum pumping speed: (a) stroke length (b) retarding forces (various types of friction, viscous, rubbing, etc., as well as buoyant factors) in the well; and (c) pumping unit geometry. In a great majority of applications, by far the most important factor in achieving maximum pumping speed is the downhole retarding force opposing rod fall. In the average well, pumping unit geometry has relatively little influence on this particular function.

When lifting fluid with a beam and sucker rod pumping system, several important facts should be emphasized. The first is that the pumping cycle is divided into <u>two</u> parts: (1) productive, and (2) non-productive. The <u>productive</u> portion of the cycle occurs only during the upstroke, when the fluid column is elevated. The <u>non-productive</u> interval takes place during the downstroke, and has as its principal function, to return pump and rods to their bottom position so the fluid column can, once again, be elevated. The faster the rods return downward through their <u>non-productive</u> cycle, the sooner they can begin the <u>productive</u> upstroke.

The upstroke is productive for at least two reasons - not only is it (1) the interval the fluid column is being elevated, but also (2) the period during which the bottomhole pump is evacuated, permitting fluid inflow into the barrel. Therefore, productivity is made possible, not only by fluid elevation during the upstroke - but also by the amount of fill-time devoted to charging the bottomhole pump. All else equal, the longer the upstroke time interval, the longer the fill-time, and the greater the amount of fluid volume entering the pump barrel, to be subsequently elevated.

Often, the operator thinks of a pumping unit lifting rods and fluid during the upstroke, and then driving, or forcing the rods downward during the return stroke. This is not the way the system works. Rods and fluid are elevated by the pumping unit during the upstroke, while the force of gravity pulls the rods downward, against upward retarding forces (buoyancy, friction, etc.), during the return stroke. This should be intuitive, since the wirelines on the unit's horsehead can only function in tension (while lifting rods and fluid), and cannot operate to push the rods down, or to drive them into compression.

PUMPING UNIT GEOMETRY AND ITS EFFECT ON ROD MOTION

In a beam and sucker rod pumping system, at least four motion characteristics are of importance. They are: (1) maximum off bottom acceleration while lifting the maximum load of rods and fluid; (2) maximum off top acceleration as the carrier begins the downstroke; (3) the time interval to make the upstroke- i.e., fluid fill-time; and (4) maximum downstroke velocity and the time interval to make the downstroke. As a reference, constant angular velocity is assumed at the crankshaft.

Broadly speaking, current beam type pumping geometries fall into two classes: (1) the Class I lever - which is a rear-mounted, pull-down system with the fulcrum at mid-beam, represented by the traditional conventional unit, and (2) the Class III lever - a front-mounted or push-up geometry, similar to the air balance and Mark II units, where the fulcrum is located at the rear of the beam (Fig. 1). The air balance and Mark II are sometimes referred to as reverse geometry units.

In order to help simplify a complex subject, rod and fluid load on the upstroke, and buoyant rod load on the downstroke will, momentarily, be considered as concentrated masses equal to their respective weights - i.e., an <u>inelastic</u> polished rod load both up and down.

Polished Rod Acceleration of Different Geometries

Because of their crank and pitman placement, the Mark II and air balance on the well-side of the fulcrum, and the conventional unit on the off-side, these two lever systems have polished rod acceleration characteristics that are diametrically opposite (Fig. 2).

Its cranks turning with constant angular velocity, the conventional unit (Class I system) makes its <u>BOTTOM</u> polished rod reversal with relatively <u>HIGH</u> acceleration, and its <u>TOP</u> reversal with relatively <u>LOW</u> acceleration.

In the Mark II and air balance units (Class III lever systems), acceleration characteristics are reversed. The front-mounted or push-up system comes off <u>BOTTOM</u> with <u>LOW</u> acceleration, but makes its <u>TOP</u> reversal somewhat faster than the conventional unit.

As a reference, the motion of the two lever systems - Class I and Class III - can be better understood if compared to simple harmonic motion (SHM).

For the sake of illustration, suppose the polished rod is moved up and down with simple harmonic motion. This means that maximum acceleration occurs as the polished rod starts upward, off BOTTOM, and the maximum downward acceleration occurs as the rod starts downward, off TOP - and the value of both accelerations are equal. In simple harmonic motion, maximum upstroke velocity is equal to maximum downstroke velocity (both occurring at mid-stroke), and the time interval to make the upstroke is the same as the interval to make the downstroke. This type of theoretical, reciprocating, motion is called simple harmonic motion, and would occur if the pitmans were infinitely long compared to the crank length. SHM is used simply as a reference. In the real world of beam pumping units, however, simple harmonic motion is not achieved, nor necessarily desirable.

Looking first at the conventional unit with its cranks turning with constant angular velocity - all else equal - it accelerates upward, off bottom, with its maximum load of rods and fluid faster than simple harmonic motion; but at the top of the stroke, it moves the carrier bar downward with an acceleration lower than that of simple harmonic motion.

Class III lever systems, like the air balance and Mark II, have reversed motion characteristics. These units move the maximum load of rods and fluid, upward, off bottom, with less than simple harmonic acceleration - while at the top of the stroke, the carrier bar starts downward with acceleration greater than that of simple harmonic motion.

Assuming a concentrated mass, peak polished rod load is controlled by the magnitude of off BOTTOM acceleration. The greater its value, the greater the peak polished rod load (all else equal) with an attendant increase in rod stress and unit structural loading. In lifting the maximum load of rods and fluid off BOTTOM, the inertial component ADDS to the static weight. Across the TOP reversal, the inertial component SUBTRACTS from the buoyant weight of the rods. In other words, the BOTTOM reversal LOADS the polished rod and structure to their peak value, while the TOP reversal UNLOADS rod and structure to their minimum value.

Unit Symmetry

In addition to the off BOTTOM and off TOP polished rod accelerations, there is another important motion factor; whether or not the unit is symmetrical or non-symmetrical, for the maximum up and downstroke velocities and time intervals are, to a degree, controlled by unit symmetry.

A symmetrical unit of any geometry, conventional, air balance, or Mark II would make its up and downstroke in approximately 180^{o} of crank rotation. This factor does not have much to do with off BOTTOM and off TOP acceleration. A symmetrical conventional unit (Class I) accelerates the maximum load of rods and fluid off BOTTOM rapidly, but moves the reduced load of rods alone downward, off top, with a lesseracceleration. A symmetrical air balance unit or Mark II would still accelerate its maximum load of rods and fluid relatively slowly off BOTTOM, and start its carrier, downward, off TOP with a greater acceleration.

A non-symmetrical unit - like the Mark II, however - with its crankshaft displaced back toward the Samson post (away from the well) - while turning in a preferred direction of rotation - makes its upstroke in more than 180^{o} of crank rotation, and its downstroke in less than 180^{o}. For instance, on the non-symmetrical Mark II, the upstroke travel of rods and fluid is made in nearly 200^{o} of crank rotation, while the downstroke covers approximately 160^{o} of crank travel. Assuming constant angular velocity at the cranks, this makes the non-symmetrical Mark II upstroke approximately 8 to 10% longer than that of a symmetrical unit, conventional or air balance, while making its downstroke about 8 to 10% faster than a symmetrical unit.

Consequently, the maximum acceleration with which the carrier bar starts its upward or downward travel is largely controlled by whether the unit is a Class I or Class III lever system - but its maximum velocities, and the time interval to make the up and downstroke, is controlled by unit symmetry - i.e., whether the unit makes its up and downstroke in more or less than 180^{o}.

It is important to observe how these motion characteristics affect the performance of different beam and sucker rod pumping systems.

MAXIMUM PUMPING SPEED AND "ROD STACKING"

For all practical purposes, the maximum pumping speed of any beam and sucker rod pumping system is reached when the minimum polished rod load approaches zero. Until "free fall" (in air) rod velocity is reached, minimum polished rod loads and maximum pumping speed are primarily controlled by well retarding forces. Since the wirelines of the pumping unit are unable to push the rods downward, maximum pumping speed results when the retarding forces in the well no longer permit the force of gravity to pull the rods down as fast as the unit's carrier bar is moved downward. This could be thought of as the "free fall" rate of the rod string. A number of forces in the well retard free fall - such as buoyancy; many kinds of friction; the rod coupling-piston effect (R-CP); and perhaps more.

For many years, a rule of thumb has been that rods fall in the average well about 70% as fast as they would free fall in air. This is often an unreliable assumption for in some wells forces of retardation permit pumping speeds significantly higher than this approximation suggests, while in others, maximum pumping rates may be even slower.

If a rod string were suspended in a deep part of the ocean, with the top rod even with the surface, the bottom rod momentarily displaced downward, and then both ends suddenly released - the rods would fall vertically downward, retarded only by the forces of friction and buoyancy. Falling under these conditions would produce little or no tendency to "buckle" or "stack" rods. This would be the limiting, or worst case of rods free falling in liquid.

In the average pumping well where the carrier bar normally exerts an upward force on the polished rod, a condition results with even less tendency to "buckle" or "stack" rods than in the buoyant, "free fall" example above.

Consequently, the limiting factor for buckling rods, under normal pumping conditions, results when the carrier bar runs away from the rod clamp and permits the rod string to fall freely as it would if dropped vertically in the ocean - but neither condition, free fall, nor restricted fall (i.e., the carrier exerting an upward force on the polished rod) would tend to stack the rods, or drive them into compression.

In the few cases where "buckling" or "stacking" of the string occurs, in general, it is because, during the downstroke, rod and pump retarding forces, near the bottom of the rod string, are greater than the retarding forces near the top. This could be caused by a tight or sticking plunger, crooked hole or excess friction near the bottom of the string, or other unusual circumstances.

When these abnormal conditions exist, and the polished rod and upper rods fall at a certain rate, while a proportionally greater retarding force acts on the pump, or lower rods, so they can't fall as fast, then buckling or stacking may result. Obviously this undesirable condition is, for all practical purposes, independent of pumping unit geometry, and occurs on applications where unusual and undesirable well conditions exist.

If retarding forces in a well act equally on all sections of the rod string, from top to bottom - like free rod fall in the ocean - there would be little or no tendency to buckle or stack rods.

In cases where relatively fast pumping lowers the carrier bar more rapidly than the fall of the bottom rods, and subsequent investigations shows worn couplings and tubing walls, it is natural to assume this is caused by a faster off top acceleration of the carrier bar "driving the rods into compression". Again, it must be remembered that the faster return stroke is not driving the rods downward, so it, in itself, cannot stack rods. Rod and coupling wear most probably results from a low, tubing dog-leg, or a tight fitting or sticking plunger, rather than a faster carrier bar return.

Unanchored or improperly anchored tubing will permit it to corkscrew (just above the bottomhole pump), or buckle, as the fluid load is removed during the upstroke, resulting in tubing seizing the lower rods. This condition frequently abraids rods, couplings, and tubing walls, suggesting the wear occurs because of a faster downstroke. Actually, the low rod coupling and tubing wear was probably caused from a low, tubing dog-leg, tight or sticking plunger, paraffin, unanchored tubing, a slipping anchor - or other causes.

In a majority of pumping applications, maximum rod loading is a more critical and important factor than free fall pumping speed. Consequently, lower off bottom acceleration tending to reduce rod and structural load is normally of much greater importance than free fall pumping which is a consideration in but a small number of cases.

Another important point is not that one type of beam unit moves downward, off top, rapidly, while another moves slowly - rather it is that one pumping geometry accelerates downward, off top, somewhat faster than another - all else equal.

"Free fall" pumping limits occur, even theoretically, only in shallow wells. In medium to deep wells, the weight of the falling rods relative to the forces of retardation are generally so great as to render any influence of pumping unit geometry on maximum pumping speed academic.

If well retarding forces are normal and evenly distributed up and down the rod string - pumping unit geometry and a faster downstroke will have little effect on rod stacking, buckling, or on maximum pumping speed.

On the other hand, the faster downstroke rod motion provides several positive advantages, a number of which will be discussed below.

MAXIMUM PUMPING SPEED, PRODUCTIVITY, AND ROD LOADING

Obtaining maximum productivity assumes a pumping unit is designed to lift all the fluid available at the well bore; or stated another way - in this discussion, the bottomhole pump's volumetric displacement is assumed greater than the rate of fluid inflow.

Superficially, it might appear that the unit geometry pumping the greatest number of strokes per minute would automatically produce the most fluid. Interestingly enough, that's not necessarily the whole story.

All else equal, productivity of a beam and sucker rod pumping system is a function of at least three important variables - not just one: (1) surface stroke length and strokes per minute - i.e., maximum pumping speed; (2) net plunger travel and pump diameter; and (3) bottomhole pump fill-time.

Maximum Pumping Speed

It has been estimated that no more than 4 or 5% of all beam and sucker rod applications operate at their maximum "free fall" pumping rate. Perhaps half, or even more, of these high speed pumping applications are overloaded either torsionally, structurally, or in the rod string - and good field practice suggests that pumping speeds be reduced so that all components of the system operate within their rated capacity. Thus, in examining maximum "free fall" pumping speed, perhaps no more than 2 or 3% of all pumping wells are required to operate in this unique category. As previously mentioned, in most cases, maximum "free fall" of the rod string is primarily controlled by forces of retardation in the well, rather than by pumping unit geometry.

Occasionally, the Mark II and the air balance units, with their higher off top accelerations, are faulted for having reduced, maximum pumping speeds, when compared to other beam type geometries such as the conventional unit. Theoretically, when handling an inelastic, concentrated mass, this may be so - but in actual field practice, reverse geometry units have achieved some unusually high pumping rates as outlined in the following example.

L. Douglas Patton, an experienced and knowledgeable student of beam and sucker rod pumping technology, illustrates how much more important well retarding forces are on maximum pumping speed than unit geometry. In his paper, "CRITICAL PUMPING SPEEDS IN BEAM PUMPING UNITS", using accepted industry formulation, Patton predicted: "On a shallow well in South America (Mene Grande Oil Corporation, Taparito Field, Lagunillas, Zulia, Venezuela, S.A.; Well No. RD716), the maximum pumping speed for an 120" stroke Mark II would be 13.1 SPM, with an average polished rod velocity of 263 FPM". However, Patton goes on to state that he "actually observed this particular unit pumping 20 SPM (400 FPM) - nearly 7.0 SPM or over 50% faster than predicted. The wells were producing 10 to 12 degree API oil through 4" casing for tubing, and using straight 1" rods with slim hole couplings".

This particular Mark II, pumping 20 - 120" SPM and developing 400 ft. of polished rod travel per minute, may be close to a record for all beam and sucker rod pumping unit types. Apparently, the Mark II's higher off top acceleration, and faster downstroke velocity, were of little hindrance in achieving this extremely high pumping speed.

Several years ago, a major oil company purchased a 144" stroke Mark II unit, for a 7,250 ft. well in East Texas. Using the (then) currently accepted minimum load formulation, the manufacturer determined that maximum pumping speed, before the minimum load reached zero, would be 7.5-8.5 - 144" SPM. Not knowing of this supposed "limitation", and desiring additional fluid, the operator actually drove the unit as high as 14 - 144" SPM for several days with a resulting minimum polished rod load of approximately 5,500 lbs. - indicating if unit, prime mover, and rod string could safely accommodate the loads, pumping speed could have been increased another 3 or 4 strokes per minute.

Why this discrepancy of nearly 100% in predicting maximum pumping speeds with the Mark II, whose carrier bar, like that of the air balance unit, accelerates downward, off top, faster than that of a conventional unit? Obviously, two important factors were not considered in the predictive formulation. One was, with a rod string weighing in excess of 15,000 lbs. (in air), the upward force of retardation opposing rod fall was relatively small - making the resulting downward force on the rod string great enough that the minimum load would be significantly higher than predicted. Another factor that oversimplified predictive formulation overlooked was assuming the rod string to be a concentrated mass. In deep wells, this can distort predictive (maximum) pumping speeds by a significant amount.

As noted, maximum beam and sucker rod pumping speed occurs when the minimum load approaches zero. If the rod string were considered inelastic, the simple formulas for predicting maximum speed might have been more accurate. What occasionally occurs is that a harmonic stress wave in a reverse geometry pumping application may be in the proper phase relationship to reinforce or elevate the minimum load, rather than reduce it. Thus, instead of contributing to a minimum load, approaching zero, the spurious harmonic may act in the opposite direction to actually raise the minimum load, and increase (potential) maximum pumping speed. Normally, the situation would occur in applications where the minimum load is not defined by the point at which rod contraction is completed near the beginning of the downstroke. In the application above, the faster off top acceleration of a Mark II could have actually contributed to a higher maximum pumping speed.

On Page 454 of the API "SUCKER ROD PUMPING SYSTEM DESIGN BOOK" (API Bulletin 11L-3), to lift 600 BFPD from 8,000 ft., with a 120" stroke conventional unit, driving a 1.75" plunger diameter, the minimum polished rod load is 7,990 lbs. Using identical formulation (solution of the wave equation) for a Mark II, with the same rod string, lifting the same fluid, the 120" stroke Mark II predicts a minimum load of 9,276 lbs. - i.e., 1,286 lbs. higher than that of the conventional unit - yet the Mark's off top acceleration is measurably faster than that of the conventional unit.

In Patton's paper on critical pumping speeds, he further states:

> "More often than not, the critical pumping speed of a particular system becomes academic."
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> Later noting that:
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> "The important consideration in rod pumping is not how fast a pumping unit can drop rods, but rather how much the beam system can pump per day. Because a certain maximum pumping speed is predicted doesn't mean that a particular pumping geometry under actual field conditions will be limited to this predicted speed."

A faster off top acceleration, and higher downstroke velocity, may not necessarily result in higher maximum pumping speeds - but in a majority of pumping applications, neither is maximum practical pumping speed, and production, appreciably reduced because of a more rapid downstroke.

Net Plunger Travel

With a given surface stroke and pumping speed, it would seem that bottomhole pump displacement, or net plunger travel, might be the same for all pumping unit geometries. Such is not the case. By varying surface geometry to effect a certain motion pattern, such as a faster downstroke, and a slower, bottom, rod-reversal rate, it is possible to significantly increase net plunger travel, per stroke, in many cases, without appreciably affecting polished rod loads.

One of the first students of beam pumping technology to recognize this effect was William Corey, who presented a paper to the American Society of Mechanical Engineers in Tulsa, Oklahoma, in the early 1950's. Corey states that the front-mounted (Class III) unit often, "serves to aid overtravel without adding to the rod stress that might be produced".

Because of its faster downstroke and slower velocity change across the bottom reversal, the Mark II tends to provide greater net plunger travel in many applications, with the same, or even a lesser, peak polished rod load.

In a rigorous and comprehensive major oil company field study comparing Class I (conventional) and Class III (Mark II) type pumping units, alternately over the same well under approximately the same conditions, the results showed a measurable increase in productivity in favor of the Mark II. The engineering report stated: "The combination of the greater velocity on the downstroke and the slower velocity change across the bottom reversal apparently causes more plunger travel. This, of course, would create more net effective (plunger) stroke", (OIL & GAS JOURNAL, December, 1960).

Several years ago, SUCKER ROD RESEARCH, INC. (SRI), Kansas City, Missouri, after determining net plunger travel for different pumping unit types by solving the wave equation applied to sucker rod pumping, showed that there were many areas of the pumping spectrum where Mark II geometry produced between 8-10% additional net plunger travel over comparable conventional pumping equipment, while operating with the same surface stroke length and strokes per minute.

H. E. Gray, a distinguished mathematician for the Shell Oil Company, presented a paper entitled, "KINEMATICS OF OILWELL PUMPING UNITS". In this presentation, Gray shows where the front-mounted unit often generates as much as 10% more net plunger excursion than a regular, rear-mounted unit. In his conclusion, Gray states:

> "Pumping unit design exerts a significant influence on the polished rod loads, PLUNGER STROKE, and torques which are obtained during the operation of the sucker rod pumping system."

In another major oil company study, the following statement was made:

> "The limits of the pump stroke for the Mark II and conventional units are determined in which an appreciable amount of difference in (plunger) stroke exists. The Mark II gives greater total stroke because of greater overtravel at the bottom of the stroke."

These and similar studies have shown the Mark II (Class III push-up system) often tends to increase net plunger travel above that of other pumping unit geometries, over a broad range of pumping applications. Admittedly, some of the reasons for this characteristic are complex, and can only be accurately determined and understood using the powerful mathematical model of the wave equation applied to sucker rod pumping. In general, however, the increased net plunger travel of the Mark II results from a faster downstroke, with a longer dwell time across the bottom reversal. Both theoretical and practical studies have proved this to be true under most pumping conditions.

Following is an explanation, admittedly oversimplified, of this unique pumping characteristic. At first glance, it would seem that a more rapid rod reversal rate, over bottom, would provide the downhole plunger with maximum overtravel and, consequently, greater net plunger stroke - i.e., "whipping" or "yo-yoing" the rods. Generally, this is not the case. The two dominant factors controlling bottom overtravel and maximum plunger stroke are: (1) a faster downstroke, and (2) longer dwell time over the bottom of the stroke.

Since the kinetic energy of a falling mass system is a function of the square of its maximum velocity (K.E. = $\frac{1}{2}MV^2$) - and since the system cannot store up this increased kinetic energy over the bottom reversal, but must give it up as bottom overtravel - the faster the downstroke, the greater the potential that exists for increasing overtravel. This may be intuitive, for if a weight is fixed to the bottom of a spring, and the spring lowered slowly for a given distance - on reaching the bottom of the stroke, the inertia of the weight will continue moving it downward a short distance, in its overtravel.

Lowering the same spring and weight system, rapidly, through the same distance as before, the amount of overtravel experienced by the weight will be considerably greater, as the top of the spring is stopped at the bottom of its stroke. The greater amount of overtravel, and increased net plunger travel, in the second case, results from a faster downstroke providing increased kinetic energy to the string, which is given up across the bottom reversal.

Since the Mark II makes its upstroke in approximately 200 degrees of crank rotation, it must make its downstroke in approximately 160 degrees. The symmetrical, conventional, or air balance units make their return, or downstroke, in approximately 180 degrees of crank rotation. This means that the higher maximum downward velocity of the non-symmetrical Mark II, returning in a shorter time period, is roughly proportional to 5.6 units per second - while the symmetrical (conventional and air balance) units develop a lower maximum downstroke velocity proportional to about 4.7 units per second. By squaring the Mark II's maximum downstroke velocity of 5.6, and the conventional unit's maximum downward velocity of 4.7, it can be seen that the kinetic energy of the Mark II's falling rod string is over 40% greater than that of the conventional and air balance units.

Obviously, the rod string with the most (downstroke) kinetic energy - and having to give up this energy on reversal - would tend to have measurably greater overtravel, especially if the rods were to delay longer at the bottom of the stroke. In making its bottom rod reversal (the lower 20% of the stroke), the Mark II cranks turn through an arc of approximately 133 degrees (267 degrees to 40 degrees) - while the conventional system making its bottom reversal (20%), travels but through 95 degrees (130 degrees to 225 degrees) of its crank rotation. Not only is the increased kinetic energy of the Mark II over 40% greater than that of the symmetrical (conventional and air balance) units, but the Mark II dwell time, across the bottom of the stroke, is also increased by nearly 30% - permitting the rods to reach out to a greater length under normal pumping conditions. This feature tends to maximize Mark II bottom overtravel, with resulting increased production for many pumping modes.

To further emphasize the dramatic effect that pumping unit geometry has on plunger travel, an equivalent comparison was made between two different pumping unit geometries - Unit A and Unit B - shown in Fig. 3. These two pumping unit geometries were applied to the same application - pumping 14 - 144" SPM with a 1.75" plunger from 7,290 ft., off bottom, with a standard API-85 rod string. The fluid level stood at 7,000 ft.; the specific gravity is 1.0.

The same mathematical model was used to determine plunger travel (API Solution of the Wave Equation) - and the only changes were in the kinematic constants which defined the particular pumping unit geometries - Unit A and Unit B. Unit A has a slower downstroke and less dwell time across the bottom of the stroke; Unit B has a faster downstroke and more dwell time.

It can be seen that the production per day for Unit A is 634 barrels - while under identical conditions, the daily production for Unit B is 740 barrels (at 100% Volumetric Efficiency) - YET NOTHING HAS BEEN CHANGED EXCEPT THE GEOMETRY OF THE PUMPING UNIT. In other words, this substantial increase in plunger travel of Unit B is brought about entirely by its geometry providing a faster downstroke with increased dwell time across the bottom reversal.

Several years ago a major oil company, using the most advanced predictive techniques, studied this subject in depth. In comparing the Mark II to other beam geometries, across the entire spectrum of pumping, the report concluded the section on productivity by stating:

> "Difference in pump stroke up to 10% exist between the Mark II and conventional unit designs. The Mark II produces a longer (pump) stroke, at speed and fluid load conditions most common in field use. Conventional design produces a longer (bottomhole) stroke only at very high speeds, which are seldom reached in practice."

Thus, in determining maximum productivity of a beam and sucker rod pumping system, not only must maximum pumping speed (for a given stroke length) be considered - but also the net plunger travel per stroke. A beam pumping unit with a 10% slower pumping speed, but with a 10% increase in net plunger travel, would produce the same amount of fluid per day as a unit, pumping faster, with a proportionately shorter plunger stroke.

Admittedly, the following is an over-simplification of a complex subject - but to a degree, pumping unit geometry has some bearing on maximizing the top overtravel of the bottomhole pump, as well as bottom overtravel. Another possible beneficial motion product of a faster downstroke, permitting a longer up cycle, is an increased, upstroke, rod recoil time. If a weight is suspended at the bottom of a spring, and the top of the spring is lifted upward, the weight will start rising and rise until it, too, has moved upward a certain distance. But, the longer the time interval of the upstroke, and the greater the amount of recoil time, the higher the position the weight, or the bottomhole pump, will attain - tending to further increase net plunger travel. With 8 to 10% more time to make the upstroke, the Mark II provides a longer upstroke period for the rods to recoil. This may, in certain cases, provide greater, pump, top overtravel, in addition to its greater bottom overtravel, thereby further increasing plunger stroke.

Fill-Time

Another important factor in maximizing pumping unit productivity is fill-time. The only period the fluid can inflow the pump is when the barrel is emptied, and the only time in the cycle this occurs is during the upstroke, when the unit is elevating both the rods and fluid. As before, it is assumed that the pumping rate is greater than the inflow rate.

The bottomhole pump is not charged instantaneously, but is filled by degree as fluid inflows the standing valve. Thus, all else equal - the longer the time interval of the upstroke, the longer the fill-time to charge the barrel, and the greater the amount of fluid permitted to inflow during the productive cycle. Thus, in general, productivity is not only a function of the number of strokes, pump diameter, and net plunger travel, but fill-time as well.

For instance, unit "A", pumping 11 SPM, with each stroke filling the barrel to 80% of its capacity, produces no more fluid than pumping unit "B", pumping 10 SPM, approximately 10% fewer SPM - but permitting the barrel to fill to 88% of its total volume each stroke.

Assuming all the fluid is being pumped out - i.e., partially filled barrel - the longer the upstroke time interval (i.e., productive cycle), and fill-time, the greater the fluid volume charging the evacuated barrel.

By offsetting the gearbox away from the wellhead, and turning the cranks in a preferred direction of rotation, the non-symmetrical Mark II geometry makes its upstroke in approximately 195-200 degrees of crank rotation, and its downstroke in the remaining 160-165 degrees. This means, with cranks turning at constant angular velocity, the upstroke fill-time interval is approximately 8 to 10% greater than that of a symmetrical pumping unit - conventional or air balance - whose upstroke is made in approximately 180 degrees of crank rotation.

Suppose, hypothetically, that a particular unit had a relatively high maximum SPM and a substantial net plunger displacement - but the fill-time for the fluid charging the pump barrel (i.e., productive cycle) was reduced - obviously, a lesser amount of fluid would inflow the barrel.

To a degree, the long, slow, productive, upstroke of the Mark II is achieved by dropping the rods more rapidly, downward, through their non-productive return cycle.

Often the increased fill-time of the Mark II is further magnified by its greater net plunger travel. For instance, a conventional pumping unit, over a 7,000 ft. well with an API-86 rod string and an 1¼" plunger, would require 16.7 - 120" SPM to effect a bottomhole pump displacement of 400 B/D. At this speed, the unit would take 3.59 seconds to make a complete cycle, making its upstroke in approximately 1.8 seconds. The fill-time for the bottomhole barrel would, of course, be proportional to this upstroke time interval of 1.8 seconds.

Using the same mathematical model to determine plunger travel, a similar Mark II unit, over the same well, with the same rods and bottomhole pump, would only have to pump 15 - 120" SPM (because of increased plunger travel per stroke), to effect the same 400 barrel of pump displacement per day. Thus, one pumping cycle would be made in 4 seconds - i.e., 2.2 seconds up and 1.8 seconds down. Thus, the fill-time for the Mark II would be proportional to the upstroke time interval of 2.2 seconds. This means that producing under these conditions, the Mark II would have a fill-time over 22% greater (2.2 vs. 1.8) than a comparable conventional unit.

In this particular application, the net plunger travel for the conventional unit is 131.6 inches, and for the Mark II, 145.6 inches. For example, assume the volumetric efficiency for the conventional unit to be 70%, and its fill-time to be 1.8 seconds. Thus, productivity would be proportional to:

16.7 SPM x 131.6 ins. x 0.70 = 1538 ins. of fluid per min.

Since the fill-time for the Mark II would be 2.2 seconds, its volumetric efficiency, relative to that of the conventional unit, would be 86% - i.e., $70\% \times \frac{2.2}{1.8} = 36\%$.

Thus, under comparable conditions for the Mark II, the fluid inflow, per minute, would be proportional to:

15 SPM x 146.5 ins. x 0.86 = 1890 ins. of fluid per min.

Consequently, for this particular application, even though the volumetric displacement of the bottomhole pump showed 400 B/D - for both the conventional and Mark II units, the actual fluid inflow for the Mark II, considering (1) fill-time, as well as (2) net plunger travel, is 19% greater than for the conventional unit (i.e., 1538 vs. 1890). The two assumptions made are that pump displacement is somewhat greater than fluid inflow; and the inflow rates are the same for both units.

For those areas of the pumping spectrum where the Mark II has significantly greater net plunger travel than a conventional unit - to produce the same amount of bottomhole pump displacement, the Mark II obviously requires a reduced pumping speed. Pumping fewer strokes per minute - i.e., a slower pumping rate - may also tend to increase rod life by reducing the number of pumping cycles.

Normally, the faster downstroke of the Mark II through the non-productive return cycle, affords a longer upstroke, with accompanying increased fill-time - even if pumping speeds are equal. If the Mark II - because of its faster return stroke, produces greater plunger travel as well, productivity may be even further increased.

Consequently, the maximum production of a beam and sucker rod pumping system is not, as is ordinarily believed, controlled only by the maximum number of pumping strokes per minute (all else equal) - but by a combination of: (1) SPM; (2) net plunger travel; and (3) fill-time. Maximum production is a function of all three of these important variables - not just maximum pumping speed alone.

In this application, because of increased net plunger travel, and fill-time - resulting from a faster downstroke - the Mark II could pump approximately 18 to 20% slower than comparable symmetrical units, and still produce the same amount of fluid per stroke. A slower pumping speed, of this magnitude, could increase rod and surface unit life significantly.

Minimum Load

Sometimes the Mark II is faulted for having a lower maximum pumping speed because of a lower minimum load. When the carrier bar starts downward, off top, at a faster rate, isn't it going to run away from the rods sooner on a Mark II, or air balance unit, than on a conventional unit?

If the returning, downstroke, rod load acted as a concentrated mass - like a large lead ball - the carrier bars of the Mark II and the air balance units would indeed tend to run away from the load before that of the conventional unit.

In the real world of elastic rod strings however, it doesn't happen in quite this simple fashion. As the elastic rod string starts down and the fluid load is removed from the rods, the first effect that occurs - almost instantaneously - is that the stretch in the rods, occasioned by lifting and accelerating the fluid load upward - must be restored to the string, as rod contraction, at the top of the stroke before the carrier bar can run away from the descending rod mass. It is often this top-stroke rod contraction that keeps the carrier from leaving the rods.

To better visualize this idea, suppose a beam pumping unit started downward from the top of the stroke with a concentrated mass, freely hanging on its carrier bar. Obviously, there is some pumping speed that will just begin to move the carrier bar downward off top, faster than the free fall of the concentrated rod weight. This defines maximum pumping speed and zero minimum downstroke load.

If, on the other hand, the same concentrated mass was hung freely, on the carrier bar by a large spring - simulating a sucker rod string, the effect would be quite different. As the carrier bar moves downward, off top - instead of running away from the rod weight, the first thing that happens (almost instantaneously) after discharging the fluid load, is that the spring (rod string) contracts, keeping some load on the carrier bar. This rapid rod contraction, near the top of the stroke, normally prevents the carrier from running away from the rod mass, and achieving a zero minimum rod load, which might, prematurely, limit maximum pumping speed.

Consequntly, because of normal rod contraction of an elastic rod string, at the top of the stroke, the faster off top, downward movement of the Mark II and air balance unit carrier bars, does not necessarily mean that maximum pumping speed - or productivity - is limited by geometry, as it might be with a concentrated rod load.

Probable Rod Load Range Reduction

In a beam pumping application, all else equal, rod fatigue failures are controlled by three dominant variables: (1) the number of cycles; (2) the peak polished rod load; and (3) the rod load range. Reducing the number and/or the magnitude of these variables will often contribute to fewer fatigue failures, and longer rod life.

If rods are driven below their peak load limit, and within their safe allowable load range, in a beneficial fluid environment, properly handled and maintained, the rod string may achieve an infinite number of reversals, without fatigue failures. On the other hand, if rods are operated above their safe allowable load limit and/or driven beyond their safe allowable load range - all else equal - fatigue failures may be expected in a finite number of cycles. In the average well, both the rated peak load, and the safe allowable load range are frequently exceeded, which often contributes to rod fatigue failures. Examination of one of these three variables, rod load range, is important in showing how Mark II beam pumping behavior may relate to it.

Perhaps the easiest way to visualize the Mark II's possible reduction in load range is to look at a typical, simplified, example, comparing the conventional and Mark II units, momentarily forgetting harmonics.

Suppose a concentrated mass load of 6,000 lbs. of rods and 4,000 lbs. of fluid is applied, alternately, over the same application by two different types of pumping units - i.e., (1) the conventional unit, and (2) the Mark II unit. The conventional unit is elevating the load, off bottom with an acceleration greater than that of simple harmonic motion (SHM) - while the Mark II lifts its upward, (max) load of rods and fluid, off bottom with less than SHM acceleration, but returns the minimum, off top (rod) load with an acceleration greater than that of the conventional unit.

EXAMPLE 1 - Conventional Unit Load Range

An impulse factor of 1.4 is assumed - i.e., the conventional unit inertial component of the peak polished rod load is 40% of the combined static weight of rods and fluid.

$$P_c = (W_r + W_f)\,(1 + K)$$

Where: P_c = Peak polished rod load; conventional unit.
W_r = Static weight of rods.
W_f = Static weight of fluid.
$(1 + K)$ = Impulse factor (conventional unit - upstroke).

Then: $P_c = (6{,}000 + 4{,}000)\,(1.4) = 14{,}000$ lbs.

Where: M_c = Minimum polished rod load; conventional unit.

$M_c = (W_r)(1 - K)$

$(1 - K)$ = Impulse Factor (conventional unit - downstroke).

Then: $M_c = (6,000)(1 - .4) = 3,600$ lbs.

And: $R_c = 14,000 - 3,600 = 10,400$ lbs. load range; conventional unit.

EXAMPLE 2 - Mark II Unit Load Range

Since the Mark II moves upward, off bottom with 40% less acceleration than the conventional unit, its impulse $factor_{(upstroke)}$ is $(1 + .6K)$ - and its impulse $factor_{(downstroke)}$ is $(1 - 1.4K)$.

$P_m = (W_r + W_f)(1 + .6K)$ Peak polished rod load; Mark II unit.

$P_m = (6,000 + 4,000)(1.24) = 12,400$ lbs.

$M_m = (W_r)(1 - 1.4K)$ Minimum polished rod load; Mark II unit.

$M_m = (6,000)(1 - (1.4)(.4)) = 2,640$ lbs.

$R_m = 12,400 - 2,640 = 9,760$ lbs. load range; Mark II unit.

Load Range Difference Between Conventional and Mark II

$R_c - R_m = 10,400 - 9,760 = 640$ lbs. less Mark II load range.

In this typical, application - the Mark II beneficially reduces the rod load range by approximately 7% - (i.e., $\frac{640 \text{ lbs.}}{9,760 \text{ lbs.}} \doteq 7\%$). The main simplifying assumption was that the rods and fluid acted like a concentrated mass. Concurrently, the Mark II lowered the peak polished rod load by 10% to 12%

Obviously, this simple analogy doesn't happen in all wells - especially deeper ones - but in shallow to medium depth wells the rod and fluid load often behaves like a concentrated mass - and except for spurious harmonic cases, the Mark II may reduce rod load range in a number of applications. This Mark II characteristic tends to maximize rod life, and minimize lost production due to maintaining failed rods.

The reason for the Mark II's rod load range reduction may not be readily apparent. Here's a simple explanation. The maximum upstroke load of rods and fluid is a large number, and as the Mark II moves this maximum mass upward with a reduced acceleration, the reduction in the inertial component is relatively large. On the downstroke, since the load involved is the much lighter one of returning rods - subtracting the inertial component results in a smaller reduction in minimum load. In other words, comparatively speaking, the Mark II reduces the peak load more than it lowers the minimum load. In concentrated mass system, or its near equivalent, this means the Mark II will normally have a lower, and more beneficial load range.

The Mark II has an off bottom (upward) acceleration approximately 40% less than that of the conventional unit, and approximately 20% less than that of the air balance unit - which, in general, affords (the Mark II) lower rod peaks, and occasionally lower rod load ranges.

One of the most definitive studies on the subject was an AIME Paper presented at the 44th Annual (National) Fall Meeting of the Society of Petroleum Engineers in Denver, Colorado. It was entitled, "DEEP HIGH VOLUME ROD PUMPING", by K. B. Nolen, Shell Oil Company, (SPE-2633). In his comparison of several pumping unit types (Conventional; Mark II; and Air Balance) considering both predicted and measured loads and pump displacement values on 26 wells in Montana, Wyoming, and North Dakota, the following conclusion was reported:

> "As pump displacement is increased, maximum stress and load range increase less with unconventional (Mark II) units than with conventional or air balance units."

When performing the same polished rod work per minute, this rigorous field study found that the Mark II beneficially reduced rod load range when compared to other types of beam pumping equipment.

In applications where the rod load range is not reduced, the Mark II's unique motion pattern and faster downstroke my provide a desirable alternative characteristic - shifting the rod load range downward toward the zero axis. In other words, a 10,000 lb. rod load range resulting from a peak load of 18,000 lbs., dropping down to a minimum load of 8,000 lbs. is more beneficial to the string than the same 10,000 lb. rod load range resulting from a peak load of 20,000 lbs. dropping to a minimum load of 10,000 lbs. This is easily seen on any Goodman Diagram.

Consequently, a faster downstroke may contribute to a desirable rod load range reduction in some cases - or if not, to an equally beneficial downward shifting of the load range in other applications.

FLUID AND GAS POUND

What about a fluid or gas pound in a well? Wouldn't a faster downstroke be more detrimental to the rods and pumping system than a slower downstroke?

Admittedly, the non-symmetrical geometry of the Mark II results in a higher average downstroke velocity, when compared to a conventional unit pumping the same speed with the same stroke length. This is because the Mark II makes its downstroke in 160 to 165 degrees of crank rotation instead of 180 degrees like the symmetrical conventional unit.

Interestingly though, the maximum velocity of the Mark II occurs in the first half of the downstroke, while the maximum velocity of a symmetrical conventional unit occurs in the second half of the downstroke (Fig. 2)! Thus, if a fluid pound occurs in the upper portion of the downstroke, the Mark II may tend to punish the rods more severely; whereas, if the pound occurs in the lower portion of the downstroke, the conventional unit rod motion may be more detrimental to the system. In any event, where possible, the causes of a fluid pound should be minimized or eliminated, regardless of the pumping unit geometry! This can be done by: (1) slower pumping, (2) shorter stroke, (3) smaller plunger - or some combination of the three. Consequently, it is not the whole story to say that because the Mark II has a faster average downstroke, it will pound more severely than a comparable conventional unit. If the impact occurs in the upper half of the downstroke, the Mark II may pound more severely - but if the pound occurs in the lower half of the downstroke, the conventional unit will experience the higher velocity and greater impact.

POSSIBLE INCREASED ROD WORK AND PRODUCTION

Another beneficial rod motion effect, resulting indirectly from a faster downstroke, which, in turn, normally lowers off bottom acceleration and peak polished rod load - can be seen by observing a typical Goodman Diagram (Fig. 5). This diagram is a simple chart which relates peak polished rod load (or stress) to safe allowable load range; i.e., the difference between peak and minimum loads. The lower the peak polished rod load, the greater the safe allowable load range that can be tolerated without fatiguing the rods.

By observing Fig. 5, it can be seen that for a peak polished rod load of P_c, the safe allowable load range is R_c, or 20 units. By employing geometry, such as a Mark II, with low off bottom acceleration, the peak polished rod load may be reduced by some 10%, down to P_m, which has a greater rod load range, R_m, or about 25 units. As a result, this 10% decrease in peak polished rod load effected a 20% increase in safe allowable load range for this particular application.

By constructing two similar dynamometer cards having these two respective safe allowable load ranges (R_c = 20, and R_m = 25) - with the same card length; i.e., the same stroke length - it can be seen that the safe work area of card R_m is substantially greater than that of card area R_c. This means, all else equal, that a greater amount of safe work can be delivered to the rod string by a pumping unit which develops a lower peak polished rod load - without exceeding the safe allowable load range of the rods. For instance, in this case, a unit pumping the same SPM and with the same stroke length could employ a larger pump, perform more polished rod work, and lift more production as a result of simply lowering peak polished rod load and being able to safely tolerate a greater load range.

CONCLUSIONS

Is a faster downstroke in a beam and sucker rod pumping unit, such as the Mark II, good or bad?

1) Doesn't the faster downstroke of the Mark II limit maximum pumping speed and, hence, production? It has been suggested that maximum "free fall" pumping is not even a consideration in perhaps 98% of all applications. If the Mark II and air balance units have acceptable pumping characteristics in perhaps 98 out of 100 applications - let's not be unduly concerned about the odd two!

   Since the pumping unit with its wirelines can only lift the <u>productive</u> load of rods and fluid, but cannot push the rods back down - generally, the most important factor in achieving maximum pumping speed is the downhole retarding force opposing rod fall - not the geometry of the pumping unit resulting in a faster downstroke.

   As an example, if a lead ball (equivalent to the well load), is hung on a 64" conventional pumping unit, the machine could run 40.24 - 64" SPM in air <u>before the carrier began to run away from the weight</u>. Obviously, when zero minimum load is reached at any slower pumping speed, for a 64" conventional unit, than 40.24 SPM, this indicates an up-thrust, frictional and buoyant force, in the well, opposing or retarding the fall of the rods.

   <u>Consequently, until the free fall pumping rate of rods in air is reached, any lesser pumping speed results from retarding forces in the well, such as friction, buoyancy, etc. - not in the geometry of the pumping unit!</u>

2) What about a faster downstroke driving the rods into compression? Generally speaking, the principal way a faster downstroke can stack or damage rods, and drive them into harmful compression is when a tight fitting plunger, or dog-leg at the bottom of the hole, etc., restricts the free fall of the bottom rods, relative to the fall of the top rods. This is (hopefully) an unusual consideration, and affects all pumping unit geometries - not necessarily those having a (comparatively) faster downstroke such as the air balance and Mark II. Wirelines can't drive rods, or anything else, into compression.

3) When fluid or gas pound occurs, doesn't the faster downstroke of the Mark II punish it, and its rods more severely than that of a conventional unit? If the pound occurs in the first half of the downstroke, the Mark II's higher velocity results in a more severe fluid pound than a comparable conventional unit would have. On the other hand, if the pound occurs in the last half of the downstroke, the conventional unit with its higher velocity would produce a more severe fluid or gas pound than the Mark II. Hence, the faster downstroke doesn't necessarily punish the Mark II or air balance units more severely - the magnitude of the impact depends on where in the downstroke the pound occurs.

4) A more rapid downstroke through the non-productive part of the cycle, makes practical the lifting of the heavy upstroke, productive, load of rods and fluid with a lower average velocity - tending to reduce and make more uniform peak upstroke forces. It also makes feasible a longer rod recoil time, occasionally maximizing top overtravel of the pump which would tend to increase net plunger stroke.

5) The faster, non-productive downstroke helps make possible the longer fill-time during the slower, productive, upstroke (8% to 10% greater), often increasing production by a significant amount.

6) The faster downstroke of the Mark II, with its increased dwell time across the bottom of the stroke, tends to maximize bottom overtravel, thereby increasing net plunger travel, and further increasing productivity - as much as 10% to 15%.

7) The pumping stroke is divided into two parts: (1) the productive upstroke which elevates the fluid and evacuates the barrel, and (2) the non-productive downstroke which simply returns the rods so that the cycle can be repeated. The faster the return of the rods during the non-productive part of the cycle, the sooner the productive cycle can begin, and the longer it can last.

8) Part of the Mark II's low, off-bottom, upward acceleration rate is made possible by a more rapid top reversal. Thus, the faster off top acceleration permits the Mark II to lift the maximum load of rods and fluid off bottom with a substantially lower acceleration, thereby normally reducing rod stress and structural loading. This tends to increase rod life and decrease structural failures. Additionally, a more rapid downstroke may beneficially reduce load range - or, if not, to shift the load range downward, thereby improving significantly rod load characteristics and the amount of useful work the rods can transmit to the bottomhole pump.

9) Doesn't the faster, off top, downward acceleration of the Mark II and air balance units tend to achieve a zero minimum load sooner than the conventional unit? It would if the rod string behaved like a concentrated mass - but since it acts more like a spring, the contraction of the rod string, at the top of the stroke (as the fluid load is transferred from rods to tubing), must be given up before the Mark II carrier bar can run away from the rod clamp. In most cases, this almost instantaneous rod contraction, holds an intimate contact between rods and carrier bar that generally prevents the minimum load from reaching zero.

The beam pumping unit with an elastic sucker rod is such a complex system that it is difficult, if not impossible, to categorically state how a faster downstroke affects every application. The burden of this discussion is to show that an apparent drawback - a faster downstroke - may often provide several important, beneficial, offsetting features.

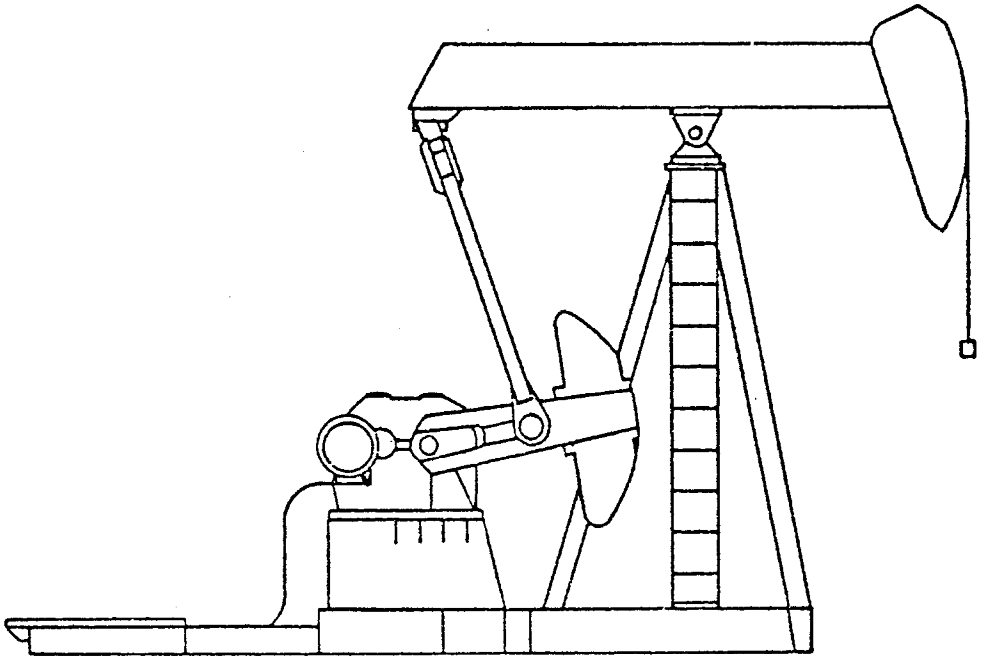
As an example, the LUFKIN Mark II pumping unit makes its downward, off top stroke relatively more rapidly than a comparable conventional unit, at least theoretically, limiting maximum pumping speed - still, one of the fastest beam and sucker rod pumping rates ever recorded was a Mark II in South America having a polished rod displacement of over 400 ft. per minute.

A faster downstroke is normally thought of as limiting production - but an M-320D-120 LUFKIN Mark II unit in North Central Texas has been in operation over 13 years and has produced as much as 5,860 B/D - close to a maximum beam pumped, production record.

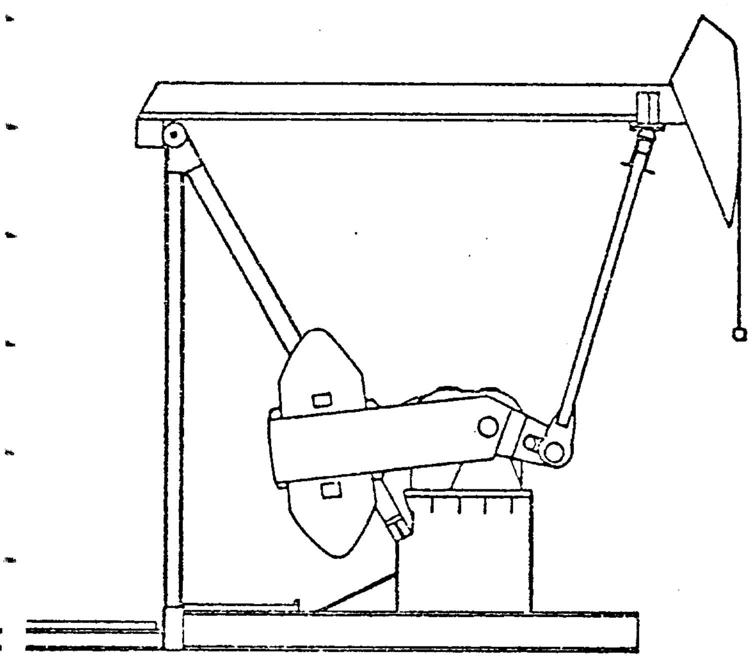
---oooOooo---

Obviously, if the operator is interested in: (1) a lower rod stress; (2) a reduced structural load; (3) more fill-time for the bottomhole pump; (4) greater net plunger travel; (5) the possibility of increased production; (6) fewer rod reversals; (7) reduced or more favorable load range; etc. - then a relatively faster downstroke of the beam pumping unit may be the solution rather than the problem.

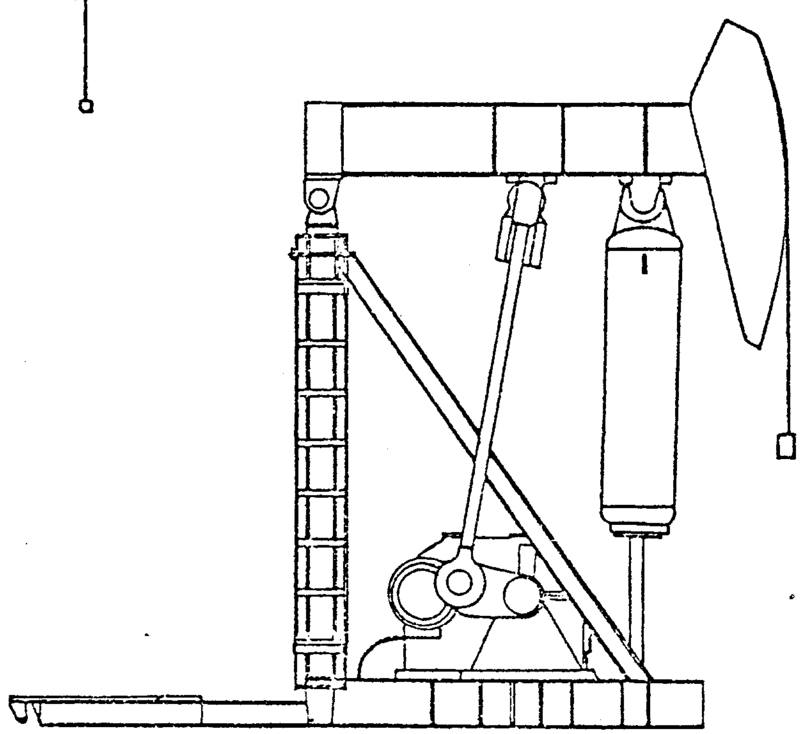
Consequently, before Mark II and air balance geometry can be faulted for a faster off top reversal, many factors must be carefully considered and thoroughly understood.



CRANK BALANCE UNIT
(SYMMETRICAL CLASS I LEVER)



MARK II UNIT
(NON-SYMMETRICAL CLASS III LEVER)



AIR BALANCE UNIT
(SYMMETRICAL CLASS III LEVER)

FIGURE 1

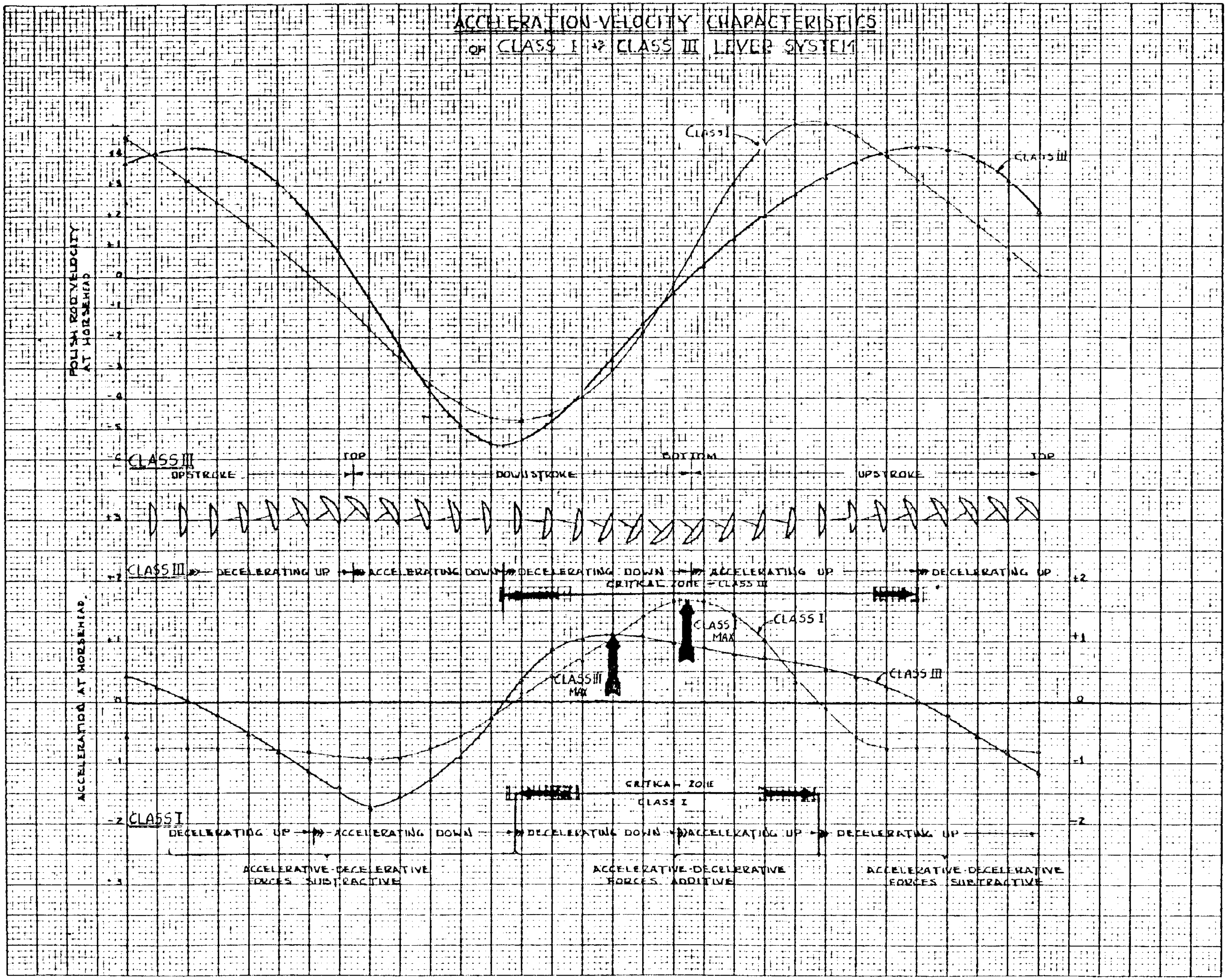


FIGURE 2—ACCELERATION AND VELOCITY CHARACTERISTICS CONVENTIONAL (CLASS I) AND MARK II (CLASS III)

UNIT A

11/08/72. 12.55.05.
PROGRAM APl11L

****** PER API RP 11L STANDARDS ******

SKR = 25428 FO/SKR = .287 N/NO = .417 WRF = 13002

ROD PERCENTAGES SPECIFIC GRAVITY = 1
1,24.93
7/8,28.21
3/4,32.49
5/8,14.36

BPD (AT 100 PCT) = 634 DEPTH = 7290 PLUNGER = 1.75
API ROD SIZE = 85 STROKE = 144 SPM = 14

FLUID LEVEL AT 7000 FT

UNIT	MAX LOAD	MIN LOAD	C'BAL	STRESS	TORQUE
CONV	28764	5750	17645	36623	813614

UNIT B

11/07/72. 10.04.22.
PROGRAM APIMRK

PER API RP 11L STANDARDS MODIFIED FOR MARK II UNIT

ROD PERCENTAGES SPECIFIC GRAVITY = 1
1,24.93
7/8,28.21
3/4,32.49
5/8,14.36

BPD (AT 100 PCT) = 740 DEPTH = 7290 PLUNGER = 1.75
API ROD SIZE = 85 STROKE = 144 SPM = 14

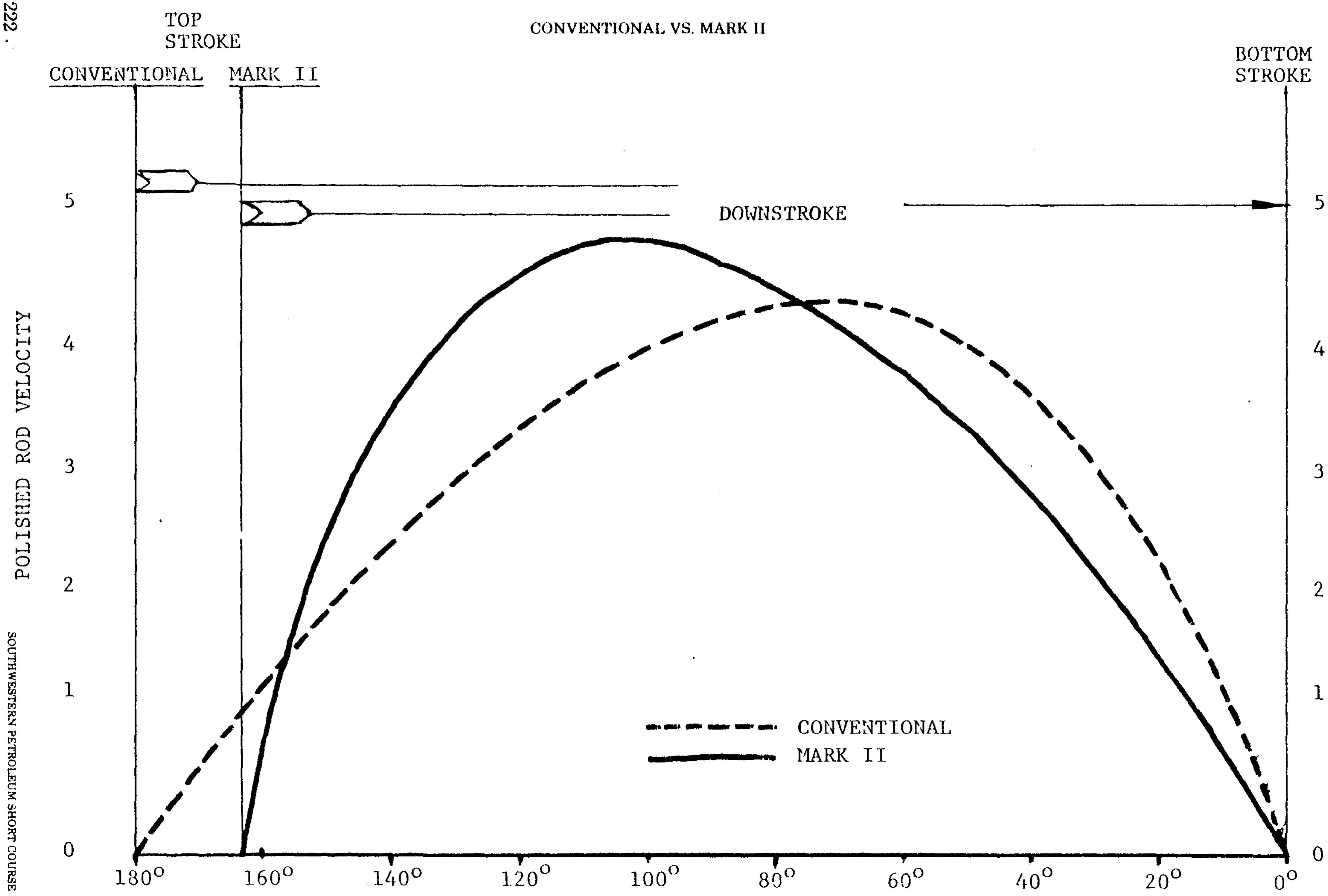
FLUID LEVEL AT 7000 FT

UNIT	MAX LOAD	MIN LOAD	C'BAL	STRESS	TORQUE
MARK	28220	6327	16260	35930	636565

FIGURE 3

COMPARATIVE DOWNSTROKE VELOCITY

CONVENTIONAL VS. MARK II



[illegible]GUR[illegible]

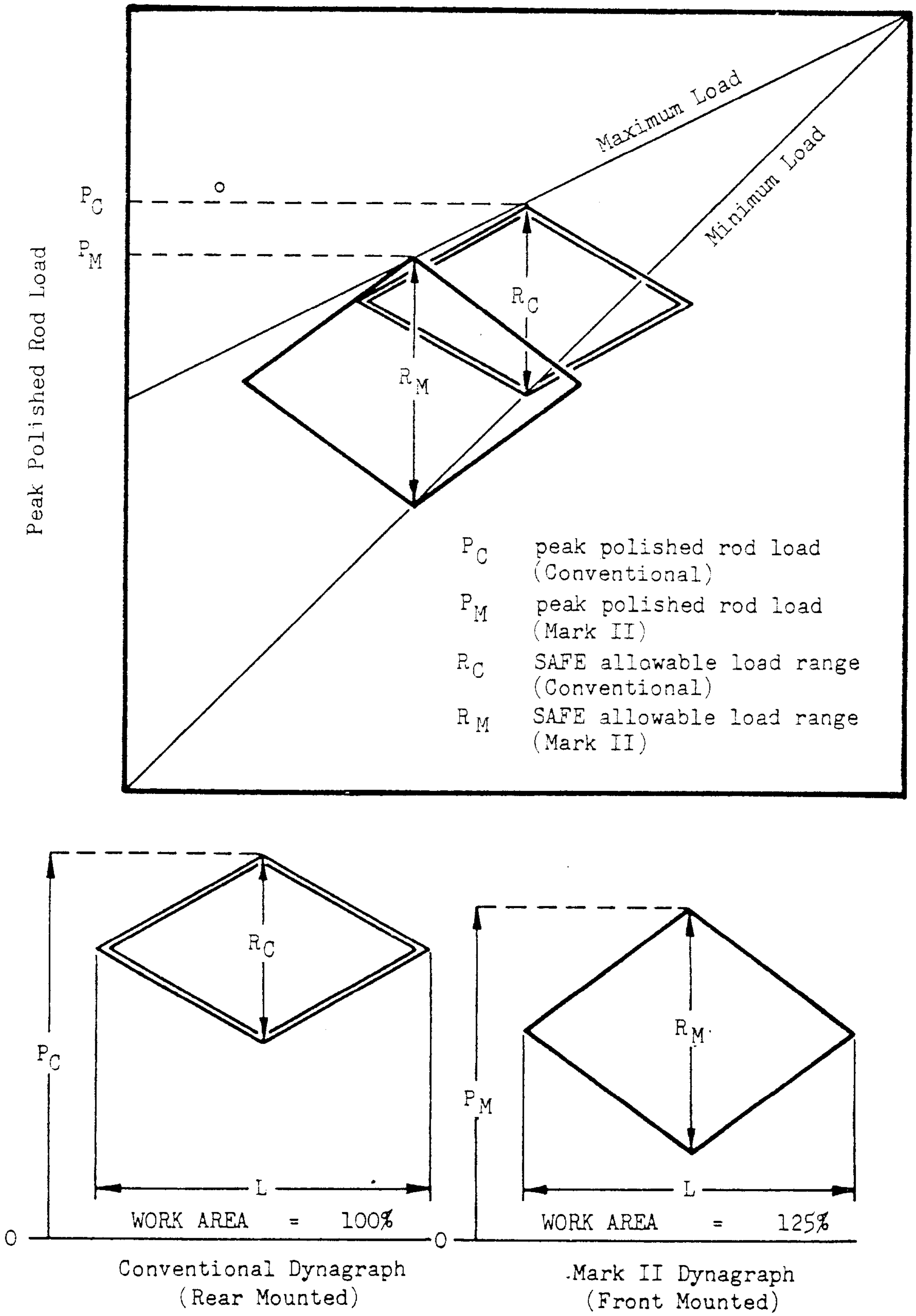

Maximum Load
Minimum Load
Peak Polished Rod Load
P_C
P_M
R_C
R_M
P_C peak polished rod load (Conventional)
P_M peak polished rod load (Mark II)
R_C SAFE allowable load range (Conventional)
R_M SAFE allowable load range (Mark II)
L
WORK AREA = 100%
WORK AREA = 125%
0
Conventional Dynagraph
(Rear Mounted)
Mark II Dynagraph
(Front Mounted)

FIGURE 5