MONITORING AND CONTROLLING ROD PUMPED WELLS USING DOWNHOLE PUMP DYNAMOMETER CARDS

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ABSTRACT

Pump off controllers have earned a place in the technology of rod pumping. Many methods exist for sensing when a well has pumped off. Most widely used are techniques based on the surface dynamometer card or motor speed or production rate.

This paper describes several methods for sensing pump off using the downhole pump dynamometer card. These include areas inside of the pump card, areas outside of the pump card, set point and liquid fillage, among others. Procedures for calibrating the controllers are described together with provisions for high fluid level recovery. Combining the liquid fillage method with variable frequency drives and eddy current drives is presented as a way of performing variable speed - no stop control.

Pump card monitors (PCMs) hold promise of being useful devices which are easy to apply and comprehend.

INTRODUCTION

Application of pump off controllers (POCs) began about 25 years ago. These controllers have proven useful in saving power and minimizing wear and tear on rod pumping equipment. These savings are realized by stopping the unit when the pump is not filling satisfactorily. The POC has gradually evolved into more than a device to sense pump off and to stop the unit. Rod load based controllers can also sense abnormal rod loads and shut the unit down before the pump and/or rods are damaged. Controllers that monitor motor speed can also prevent damage to the prime mover and gearbox. Controllers that monitor liquid rate can also prevent damage to the surface stuffing box packing. POCs sometimes increase production slightly by detecting malfunctions sooner than ordinary surveillance techniques. At this writing, about 35000 wells worldwide have been equippped with POCs.

The question arises as to why more of the approximately 600000 wells worldwide have not been equipped with controllers. A primary reason is cost because most wells are small revenue producers. These wells can not bear the expense of POCs (at least in the minds of many oil producers).

Another deterrent to application relates to mystery surrounding them and undue care required to calibrate them properly. The majority of POCs sense pump off from some feature of the surface dyno card. Surface cards are complex and have innumerable shapes. For each downhole condition, say full liquid fillage, an infinite variety of surface cards exists for different pumping speeds, pump depths, rod designs and unit and motor characteristics. The complexity of a surface card can lead to errors in calibration (setting to sense pump off) which in turn can lead to lost production and aggravation. For example the surface card of Figure 1 seems to indicate a pumped off well even though the pump card reveals that the pump is filling completely. An unwary person might set the controller to stop the unit and a loss in production would result. It is not an easy task to properly calibrate a POC knowing that infinitely many surface cards correspond to a single downhole pump condition.

The purpose of this paper is to share ideas concerning how the downhole pump card can be used to sense pump off. While creation of the downhole card is not simple, use of the pump card to sense fluid pound is. The complexity of computing the pump card can be hidden in software and hardware without troubling the user. The result is a pump off control concept that is more easily understood and applied. Hereinafter, a POC which uses the downhole pump card to control the well will be called a pump card monitor (PCM).

Oil producers began to be familiar with computed downhole pump dynamometer cards about 30 years ago. These cards have the advantage of simplicity. Only two types of cards have to be comprehended in calibrating a PCM. These are full liquid fillage and incomplete liquid fillage (fluid pound or gas interference).

With anchored tubing, pump cards that indicate full liquid fillage have roughly a rectangular shape (Figure 2). Just after the pump reaches its lowest position and starts upward, the traveling valve closes. The pump is virtually stationary while the fluid load is being transferred from the tubing to the rods. Just after the pump begins to move upward with the fluid load applied, the standing valve opens. Fluid is lifted to the surface with a somewhat constant pump load and simultaneously, liquid from the reservoir completely fills the chamber beneath the rising plunger. When the pump reaches the top position and begins to move downward, the standing valve closes. The pump is again virtually motionless while the fluid load is transferred back to the tubing from the rods. After all of the fluid load is removed from the rods, the traveling valve opens and the pump contiues downward to begin another cycle. The pump action just described creates a somewhat rectangular downhole pump card which indicates full liquid fillage (no fluid pound - no gas interference - well not pumped off). Yet the surface card corresponding to the simple rectangular shaped pump card can have a very complex shape depending upon depth, speed, rod design, unit geometry and motor characteristics.

The incomplete fillage case is shown in Figure 3. It differs from the full liquid fillage case in that the pump does not fill completely on the lifting portion of the stroke. Liquid (oil and water) only partially fills the chamber below the rising plunger. Free gas occupies the remainder of the volume. On the downstroke, free gas must be compressed before the traveling valve opens. The shape of the compression curve is determined by the pressure of the free gas. For high pressure gas the compression takes place gently as fluid load is transferred from rods to tubing (so-called gas interference). If low pressure gas enters the chamber during the upstroke, the compression takes place rapidly (fluid pound) as load is suddenly transferred from rods to tubing.

USE OF THE PUMP CARD TO SENSE PUMP OFF

There are several ways to sense pump off using the downhole pump dynamometer card. The following presentations show how certain features of the downhole card change as fillage ceases to be complete.

Inside Area (Pump Power)

Pump power is indicated by the area within the pump card trace. When a well pumps off, less pump power is required because less fluid is being lifted to the surface. Figure 4-a shows the area within the pump card while the pump is filling completely but is on the verge of pump off. Figure 4-b shows that area of the card decreases when pump off occurs. The PCM (a device which contains a digital computer) can be taught to compute pump power and to stop the unit when calculated power drops below a preselected amount. The method based on pump power has problems with high fluid level recovery. Pump power also decreases when fluid level rises. This is because the high fluid level helps lift the well thereby decreasing pump power required. Thus a PCM based on pump power might incorrectly shut the well down with a high fluid level. It therefore needs help in differentiating between pump off and high fluid level. This is discussed later.

Inside Area to Left and Right of a Vertical Line

Area inside the pump card can be used in other ways. An arbitrary vertical line can be drawn at some point in the pump card, say at mid-stroke. Pump off can be declared when area to the left of the line differs from area to the right of the line by a preset amount (see Figure 5).

Outside Area Between Downstroke Trace and Horizontal Line

Areas outside of the pump card trace also have meaning with respect to pump off. Figure 6-a shows a horizontal line drawn beneath a pump card indicating full liquid fillage. The shaded area outside of the card between the horizontal line and the downstroke trace is singled out for study. Figure 6-b shows how the shaded area increases as the well pumps off. The PCM can be taught to calculate the area and shut the unit off when the area reaches a specified amount.

Set Point Specifying Reference Load and Position

A reference point on the surface card has been successfully used to declare pump off. A similar idea can be used with respect to the downhole card. Figure 7-a shows a reference point (specified pump load and pump position) superimposed on a full liquid fillage pump card. As long as pump load at the reference position is less than the reference load, the well is considered not to be pumped off and pumping is continued. Figure 7-b shows the same reference point on a fluid pound pump card. Pump off is declared when pump load at the reference position is greater than the reference load.

Net Liquid Fillage

Net liquid fillage can be used as a basis for sensing pump off. Net liquid stroke and gross stroke are defined in Figure 8. Net liquid stroke (S_n) is identical with gross stroke (S_g) as long as the pump fills completely with liquid. When the pump ceases to fill S_n decreases and becomes less than S_g. The PCM can be taught to identify S_n. By defining pump fillage as

$$\% \text{ Pump Fillage} = 100 \; S_n / S_g$$

the PCM can cause the unit to shut down when pump fillage drops below a preset value. For example, the technician can set the PCM to shut the unit down when pump fillage drops below 80 percent. No other calibration is required and the technician does not even need to display the downhole pump card.

HIGH FLUID LEVEL RECOVERY

Even though efforts are exerted to keep fluid level near the pump, high fluid levels often occur in practice. For example a tubing leak of increasing severity can cause the fluid level to rise. The PCM should respond correctly by sensing that the well is no longer pumped off and should produce the well full time until the tubing leak is discovered and repaired. A tubing leak should be suspected if a well that normally pumps off begins to produce full time. Many POC algorithms are tricked by high fluid levels. They often shut the well down erroneously and cause a loss in production.

The effect of rising fluid level on the pump card is illustrated by Figures 9-a through 9-c. The process starts with the well pounding fluid (Figure 9-a). As fluid level rises, the well no longer pumps off and fluid load on the pump decreases because the high reservoir pressure is helping lift the well (Figures 9-b and 9-c).

A PCM algorithm based on area outside of the pump card between a horizontal line and the downstroke trace has inherent high fluid level recovery capability. Figure 10 illustrates this. Pump off is sensed when the subject area increases significantly (see Figure 10-b then Figure 10-a). Rising fluid level does not cause confusion because the subject area is essentially constant as the pump card changes from Figure 10-b to 10-c.

A PCM algorithm based on pump fillage also has inherent high fluid level recovery capability. Figure 11-a shows a well set to shut down when fillage drops below 80 percent. Fillage is 100 percent or virtually so for higher fluid levels (Figures 11-b and 11-c). Since these fillages exceed 80 percent, pumping is continued without interruption.

Fluid load on the pump is also of utility in sensing high fluid levels. Fluid load is greatest when the well is pumped off. As reservoir pressure (related to fluid level) rises, fluid load on the pump decreases (see Figure 9). A reference fluid load can be defined as the fluid load on the pump in a pumped off condition. This is roughly approximated by the simple formula

$$L_r = P_t + D \quad A_p \quad G_t$$

This is illustrated as follows:

P_t = 100 psi
D = 5000 ft
A_p = 1.767 sq in (1.5 inch pump)
G_t = 0.433 psi/ft (equivalent to fresh water)

L_r = 100 + 5000 (1.767) (0.433) = 3926 lbs.

The PCM is taught how to calculate fluid load on the downhole card. It can be instructed to allow the fluid load to decrease no more than a given amount, say 20 percent, from the reference value before sensing the high fluid level. In the example above, the PCM would decide to pump the well full time if fluid load decreased to 3141 lbs [3926 (1 - 0.2)] or less even though other algorithms indicate the well is pumped off. By serendipity, this is also a way of discerning between gas interference and fluid pound. If the well becomes very gassy, pump fillage will likely be incomplete. The large amount of gas in the tubing will also decrease fluid load. The low fluid load will cause the PCM to declare a high fluid level and to continue pumping full time even though pump fillage might have dropped below the shut down value.

The downhole pump card allows more than one POC algorithm to be in use at one time. It also allows simultaneous cross checks to insure that the well is not improperly shut down because of a high fluid level.

DIFFERENTIATING BETWEEN GAS INTERFERENCE AND FLUID POUND

Both gas interference and fluid pound result in incomplete liquid fillage. A well with gas interference should not be shut down because production will be lost. High pressure gas entering the pump leads to gas interference. This high pressure indicates that producing pressure at pump depth is not being drawn down to a low value. Hence production rate is not maximum. Fluid pound results when low pressure gas enters the pump. The low pressure reveals that producing pressure at pump depth is low so that production rate is maximum, or nearly so. Most POCs have no way of discerning between gas interference and fluid pound. Thus they shut gassy wells down when they should not and cause losses in production.

The pump card can be used to determine if incomplete fillage is due to gas interference or fluid pound. Figure 12 shows how free gas pressure affects the shape of the gas compression portion of the pump card. As pressure decreases, the curvature of the compression trace increases. In other words, the pump intake pressure corresponding to trace **a** is greater than pump intake pressure corresponding to trace **b** which in turn is greater than pump intake pressure corresponding to trace **c**. The shape of the gas compression curve is closely approximated by the polytropic law

$$P V^{n} = k$$

In deciding whether to shut the unit down or not, the PCM can compare the curvature of the compression trace on the pump card with a theoretical trace based on a preset pump intake pressure consistent with fluid pound.

Figure 13 illustrates the procedure. The pump intake pressure in the well (see the downhole card) is about 600 psi. The well has gas interference and is not pumped off. It should not be shut down even though the pump is not filling. The polytropic law is used to draw the compression portion of a pump card based on a low intake pressure of 100 psi. Note that the actual compression trace falls well below (and has less curvature than) the theoretical trace based on 100 psi. Also the actual fluid load is much less than the theoretical value (see again Figure 11). These clues suggest that the well is gassy and should not be shut off. The pump card, in principle, allows the PCM to differentiate between fluid pound and gas interference whereas a surface dyno algorithm would not.

CALIBRATION PROCEDURES

Several PCM algorithms have been presented. The manner in which these algorithms can be calibrated to a given well will now be described. Probably the best calibration procedure only involves selecting the shut - down card. Ideally, no graphical construction or special thinking will be required of the technician.

Suppose that the pump card shown in Figure 4 is selected as the shut - down condition. At a certain place in the calibration program, the technician simply hits Enter on the computer keyboard (or keypad). If the inside area (pump power) method is used, the PCM computer calculates pump power for this condition and remembers the value (12 hp). Thereafter, when pump power drops below 12 hp, the PCM will declare pump off and shut the unit down. As mentioned previously, this method needs additional logic to discern between high fluid level and pump off. For example, pump power could drop below 12 hp because the fluid level is high. The PCM should not shut the well down.

Assume the PCM is using the inside area to left and right of a mid-vertical line (see Figure 5 again). When the technician hits Enter, the PCM determines that the area to the left of the line is 378000 lb-in and that the area to the right of the line is only 216000 lb-in. Converted to a percentage, the right area is 57 percent of the left area. The PCM remembers this value. Thereafter it will declare pump off and shut the unit down when area to the right is calculated to be less than 57 percent of the area to the left. By using percentages, the PCM will likely have inherent high fluid level recovery capabilities.

Figure 6-b shows the PCM considering the area between a horizontal line and the downstroke trace. When the pump off card is identified, the PCM computes and remembers the area of 180000 lb-in. Thereafter when this area exceeds 180000 lb-in, the PCM declares pump off and shuts the unit down. As described already, this algorithm has inherent high fluid level recovery capabilities. This area should always be less than 180000 lb-in in a high fluid level condition. However, this algorithm needs additional logic to eliminate confusion caused by an intermittent hitting - down condition.

Graphical construction is required in the set point method. In the well of Figure 7, the technician would identify a reference point, say 95 inches into the upstroke and at a pump load of 2600 lbs. Pump off will be declared when the PCM determines that pump load (3800 lbs) is greater than the reference load at the preset position.

The fillage algorithm does not even require the technician to view the pump card. For example if 80 percent fillage will not constitute a damaging fluid pound, the technician will simply enter 80 percent as the shut down fillage. Thereafter the PCM will declare pump off and shut the unit down when computed fillage drops below 80 percent. For the well of Figure 8, gross and net strokes are computed to be 119 and 87 inches respectively. This indicates a fillage of

$$100\ (87)\ /\ 119 = 73 \text{ percent}$$

which is less than the preset value of 80 percent. Thus the PCM will shut the unit down. As described previously, this method has inherent fluid level recovery capabilities in most cases. When fluid level rises, pump fillage will usually increase to 100 percent which will cause the PCM to operate the unit continuously until the fluid level is drawn down to a low value again.

It is possible that a large increase in gas production can cause confusion. In this case, PCM logic can be supplemented with a separate high fluid level recovery mechanism based on fluid load and/or compression trace curvature already described.

OTHER APPLICATIONS

Classical "start-stop" pump off control is not the only application of the various pump card algorithms. Another useful scheme involves "variable speed - no stop" control with use of variable frequency drives (VFDs) or eddy current drives (ECDs). Some wells respond favorably to variable speed - no stop PCM. One well might need to pump continuously because stopping it would allow produced sand to fall back and stick the pump. Another well which has low reservoir pressure and a good PI might produce a little more oil if pumped continuously.

Another method of variable speed - no stop control has been used in the past wherein a conventional POC causes a shift to a (preset) slower speed instead of stopping the unit entirely. The pre-planned 2 speed method differs in that the technique herein uses the PCM to continually adjust pumping speed without human intervention.

Figure 14 illustrates how a PCM using the fillage algorithm behaves in variable speed - no stop control. Presume that the technician selects 80 percent as a value to be maintained (Figure 14-a). If fillage increases to 85 percent (Figure 14-b), the PCM would signal the drive to increase pumping speed to 7.6 SPM at which point the desired fillage of 80 percent is regained. If well productivity continues to increase, pumping speed will be caused to increase until a preset maximum is reached. If the unit is unable to pump the well down to the desired 80 percent fillage at the maximum allowed pumping speed, higher volume lift equipment may be needed.

Declining productivity could cause fillage to decrease below the desired 80 percent. The PCM will react by issuing the command to slow down, say to 5.5 SPM (Figure 14-c). At the lower speed, fillage will presumably return to the desired 80 percent. If productivity continues to decrease, the PCM will decrease speed further until a minimum preset speed is reached. The lower speed limit is required to insure that the unit gearbox will lubricate properly and that the VFD or ECD will not overheat.

Comparative performance with conventional start-stop POC and variable speed no - stop control with a VFD and PCM are shown in Table 1. The pump is at 4700 ft and the well is being produced with a C640-305-168 unit and a 2 - inch pump. As the comparison shows, the PCM/VFD combination produces lower equipment loading. Production rate is relatively unchanged. Conventional POC is slightly more energy efficient.

Another application (as yet untested) is to control wells equipped with internal combustion engines by combining a PCM (running the fillage algorithm) with a servo throttle mechanism. This would allow no - stop operation of the engine while protecting the equipment from fluid pound.

CONCLUSIONS AND RECOMMENDATIONS

1. Pump off control using the downhole pump card shows promise of being simple to comprehend and simple to apply.

2. It is advantageous that multiple control algorithms be used simultaneously. Historically, wells have behaved in ways not fully anticipated by humans. Multiple algorithms lessen the chance that a monitor will not react properly thereby causing a loss in production or other inconvenience.

3. Initial setup of a PCM requires more data, principally the rod design information needed to construct the pump card. Luckily this data is commonly available. Thereafter the pump card can be viewed with the simplest peripheral computer. The complex calculations have already been made in the PCM.

4. Like a conventional POC, the PCM can be confused by a rod part. When rods part, the surface card changes radically. The computed pump card becomes erroneous. Thus the rod part must be sensed (with rod load limit tests) before a pump off control decision is made. The unit will be stopped because of a rod part instead of an erroneous pump off control decision.

5. Variable speed - no stop control shows promise in a limited number of wells. The cost of the VFD or ECD is a disadvantage.

6. Continuous computation of the pump card in the PCM is helpful for reasons other than pump off control. For example, a reasonably accurate production test could be displayed by the PCM. This could be useful as a cross check on ordinary volumetric tests and as means for sensing tubing leaks.

7. The PCM gives technically correct procedures for sensing and recovering from high fluid levels. High fluid level recovery has historically been troublesome for ordinary POCs.

NOMENCLATURE

Symbol	Description	Units
A_p	Area of downhole pump	sq in
D	Depth of pump	ft
G_t	Gradient of tubing fluid	psi/ft
k	Constant in polytropic law	
L_r	Reference fluid load	lb
n	Polytropic exponent	
P	Pressure beneath pump plunger	psi
P_t	Surface tubing pressure	psi
S_n	Net liquid stroke on pump card	in
S_g	Gross pump stroke	in
V	Volume of free gas in pump	cu ft

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3. Westerman, G. Wayne: "Pump-Off Control - State of the Art," paper presented at Thirty-sixth Annual Southwestern Petroleum Short Course, Texas Tech University, Lubbock, April 19-20, 1989.

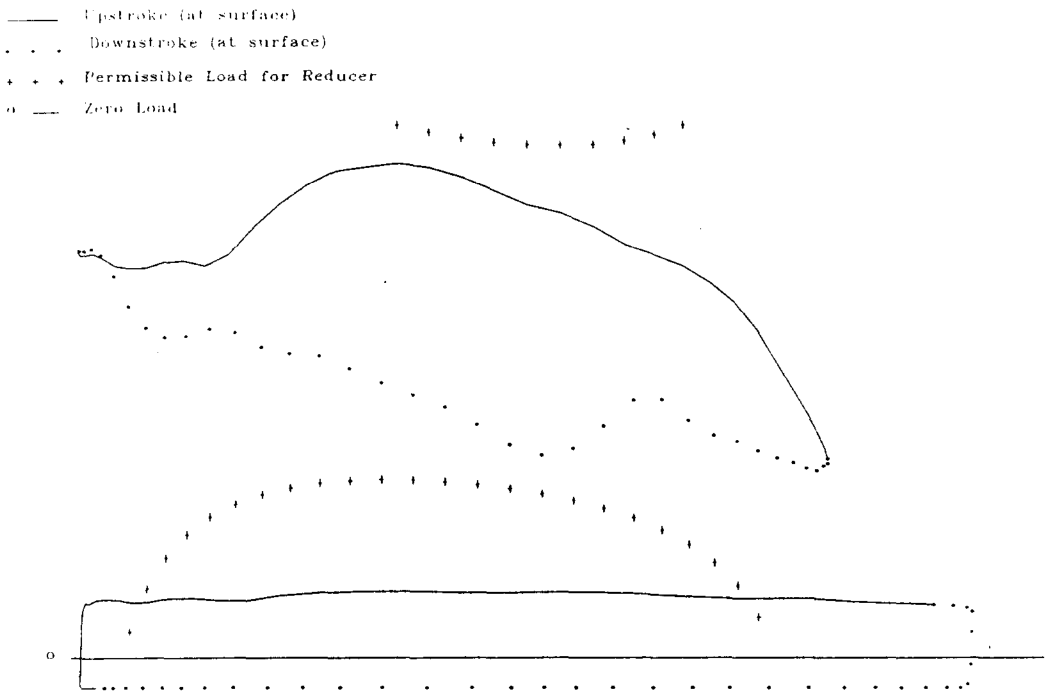
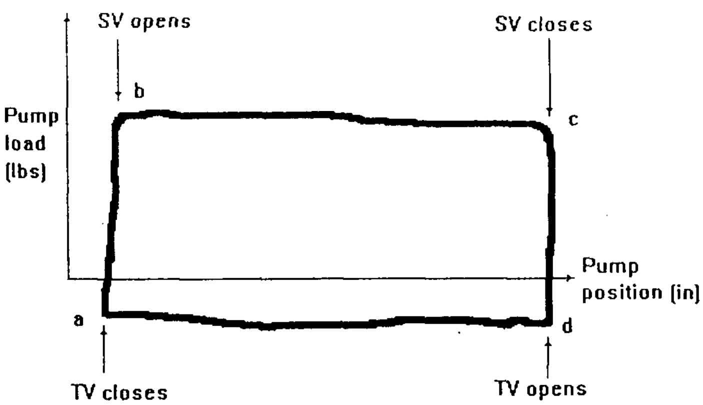
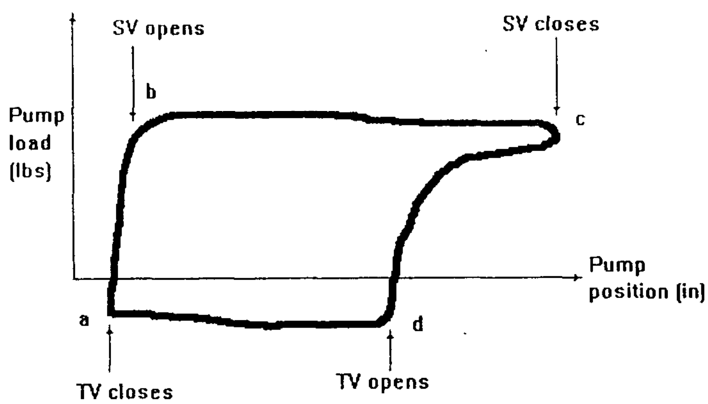


Figure 1 - Surface card showing false fluid pound



Segment a - b: Fluid load transferred from tbg to rods
Segment b - c: Fluid lifted to surface with load applied
Segment c - d: Load transferred from rods to tbg
Segment d - a: Unloaded pump descends to repeat process

Figure 2 - Pump card showing full liquid fillage



Segment a - b: Fluid load transferred from tbg to rods
Segment b - c: Fluid lifted to surface with load applied
Segment c - d: Load transferred to tbg when free gas is compressed
Segment d - a: Unloaded pump descends to repeat process

Figure 3 - Pump card showing incomplete liquid fillage

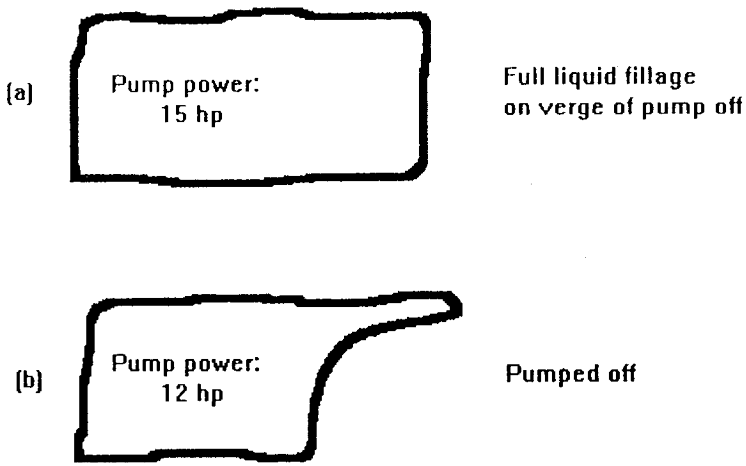


Figure 4 - Pump power decreases as well pumps off

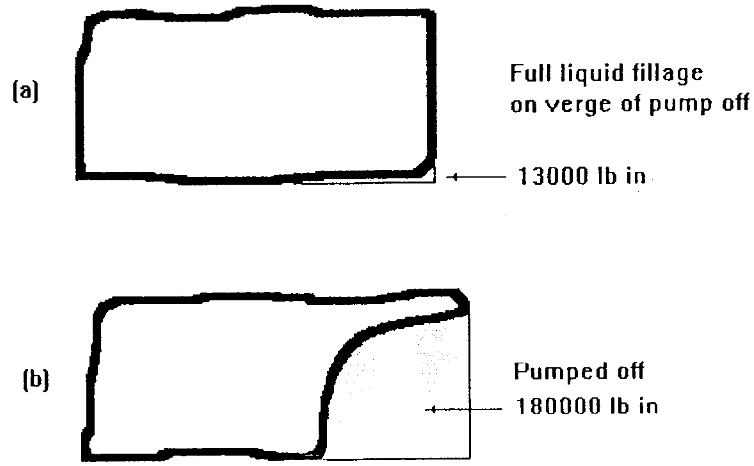


Figure 6- Pump off sensed when outside area increases to preset value

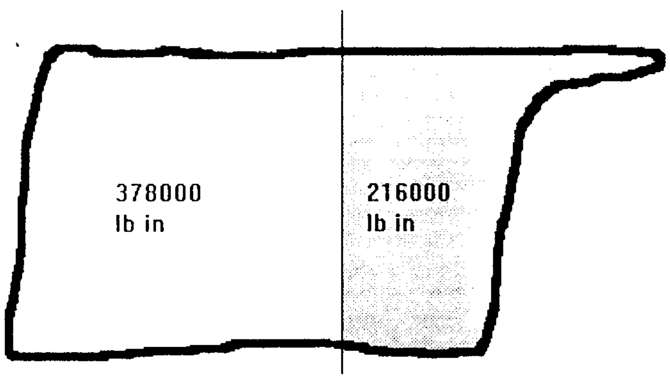


Figure 5 - Pump off declared when right inside

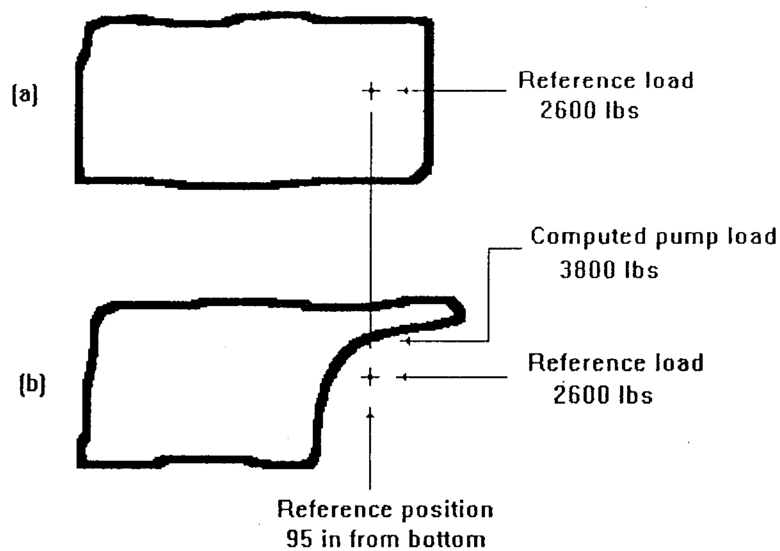
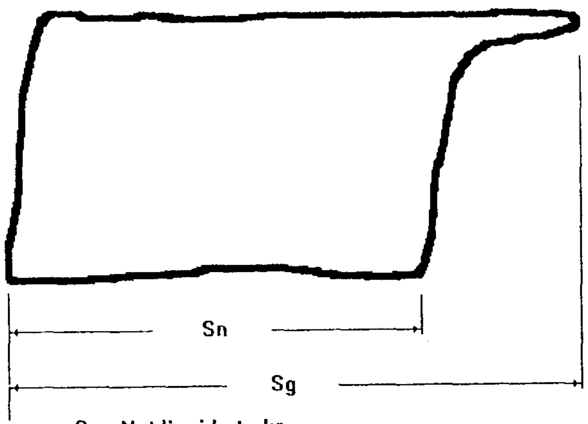


Figure 7 - Pump off declared when reference point falls outside of pump card



Sn - Net liquid stroke
Sg - Gross pump stroke

$$\text{Liquid Fillage (\%)} = \frac{100\ Sn}{Sg}$$

Figure 8 - Unit is stopped when pump fillage decreases below preset value

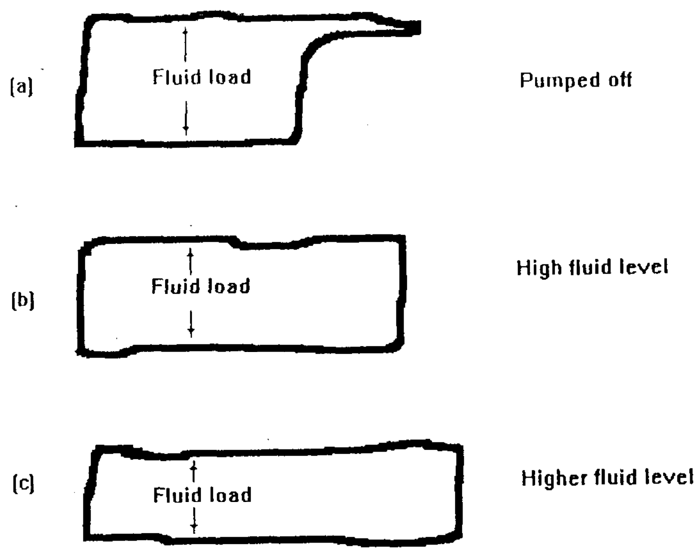


Figure 9 - Fluid load decreases as fluid level rises

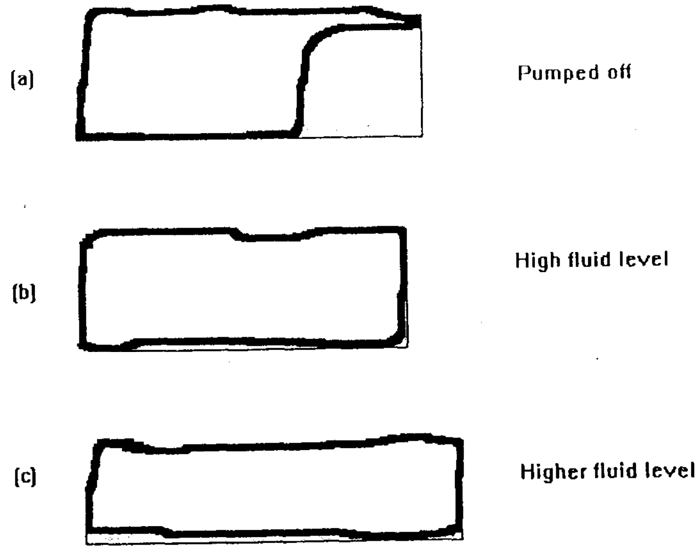


Figure 10 - Outside area change is small when fluid level is high

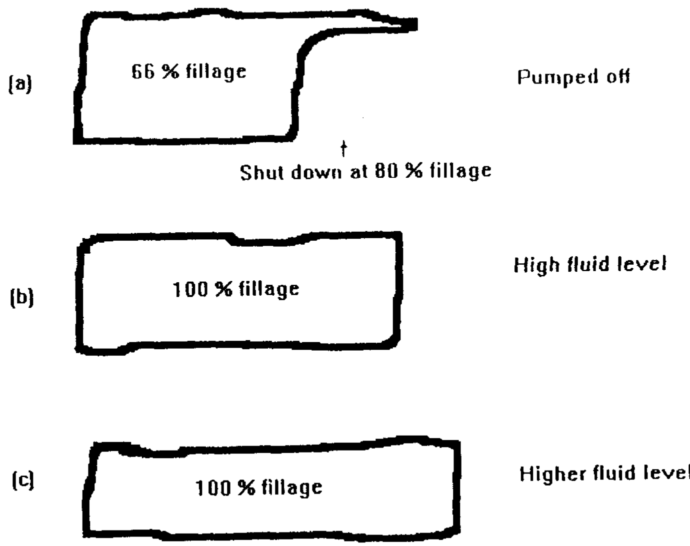
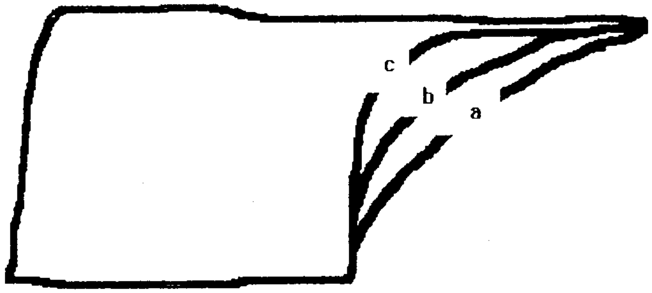


Figure 11 - Fillage usually increases to 100 percent during *high fluid level period*



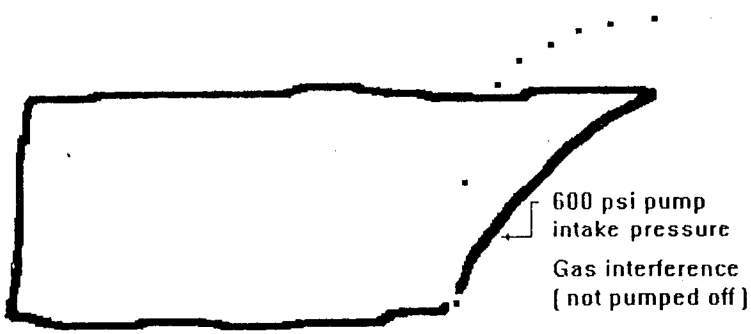
Pa is pump intake pressure corresponding to trace a

Pb is pump intake pressure corresponding to trace b

Pc is pump intake pressure corresponding to trace c

Pa > Pb > Pc

Figure 12 - Curvature of compression trace increases as pump intake pressure decreases



▪ ▪ ▪ Theoretical compression trace based on 100 psi pump intake pressure (pumped off)

$P V^n = k$

Figure 13 - High fluid level detected when gas compression trace falls well below theoretical fluid pound trace

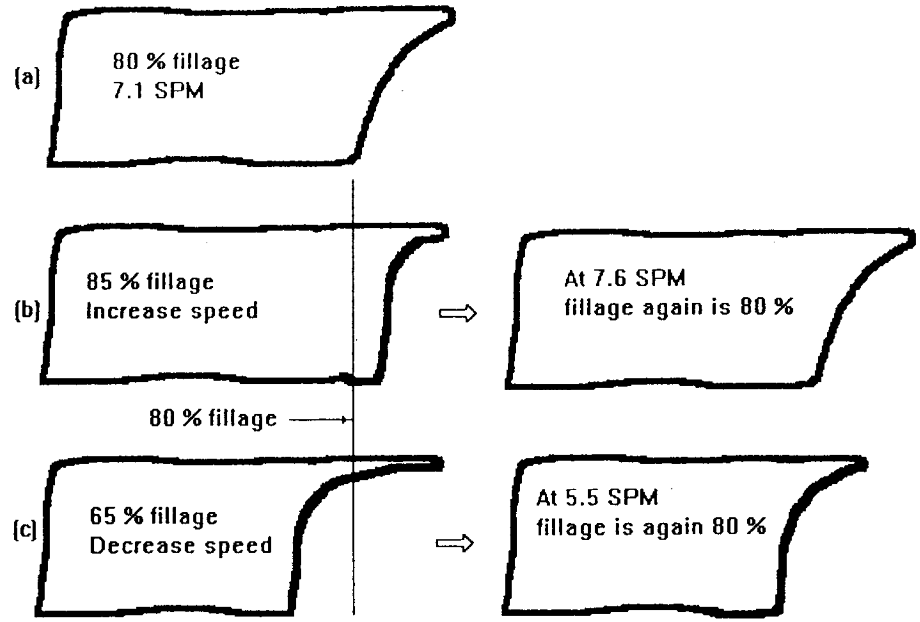


Figure 14 - Continuous control of fillage with speed changes