Analyzing Pumping Well Performance With a Computer

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INTRODUCTION

Technological Contributions

The "Golden Age" of the studies of all sucker rod pumping systems must be considered as the period from around 1927 to 1943. It was during these years that petroleum engineers such as Uren, Coberly, Marsh, Slonneger, Mills, Kemler, Sargent, Gilbert, Rieniets, and Johnson developed theories and tools, such as the polished rod dynamometer (1927), bottomhole pressure bomb (1929), pump dynagraph (1936), and the sonic fluid level sounder (1936). It was from these tools, and field tests, that our present knowledge of sucker rod pumping is based. Contributions made since 1943 represent, in a majority of cases, an enlargement, elaboration and refinement of the basic principles set up during the preceding period, in an effort to correlate the data obtained from these various instruments (dynamometers, fluid level sounders, pump dynagraphs, etc.).

A notable exception to this is the Gibbs-Neely mathematical technique" . . . developed to bridge the gap which arises when visual interpretation from a surface dynagraph is inconclusive or when quantitative downhole data are needed"[1] This new technique analyzes pumping well performance with a digital computer and, in effect, yields all the information derived from the aforementioned mechanical devices, but with the added advantage of requiring one series of measurements made at the polished rod.

Theoretical Background

The computerized analytical technique is based on a mathematical model of the sucker rod installation. The technique, using load and displacement data measured at the polished rod, develops load-displacement values for desired points along the rod string and at the pump by assuming the rod string to be a communication system transmitting instantaneous force impulses at the accoustical velocity of steel (15,000 ft/sec) from the pump to the polished rod. Strain waves initiated by the change of fluid loading upon the pump, during upstroke and downstroke are the principal forces acting upon the bottom rod, supplemented by other extraneous forces acting upon the pump and along the rod string resulting from acceleration, harmonics, friction and viscous dampening inherent in the system.

It is the function of the mathematical model to unscramble or decode the surface recording, essentially filtering out the dynamic, harmonic, and friction forces, so that quantitative deductions regarding down-hole operating conditions can be made.

The complexity of the mathematics involved requires the use of a digital computer in obtaining load-displacement information relative to instantaneous operating conditions at the pump, at desired points along the rod string and at the polished rod. The computer program requires the polished rod data be given to it in the form of a Load-Time history and a Displacement-Time history. This requirement lead to the development of the Delta II Dynamometer.

Delta II Dynamometer

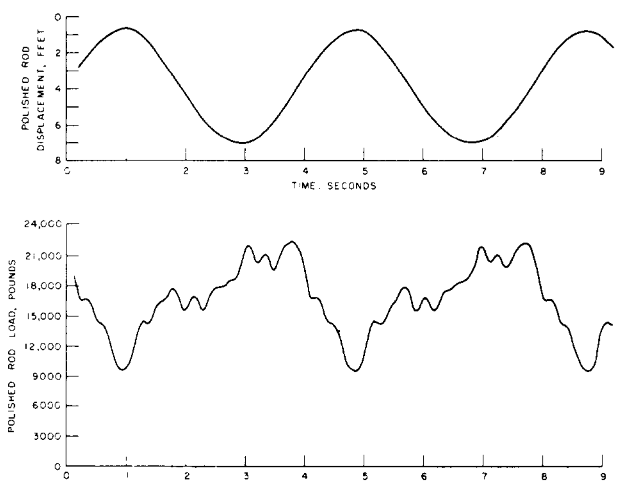
In application, the polished rod data is recorded on the strip chart of a Delta II Dynamometer which consists, basically, of a dual channel carrier-amplifier recorder, a strain gage-type load cell (for the polished rod loads) and a displacement transducer (for the instantaneous polished rod position). Eichmeier[2] and Herbert[3] have described the Delta II Dynamometer, its components and its use in detail; suffice it to say, that the polished rod data recorded at the well site (Fig. 1), pertinent well data concerning downhole equipment, and known operating conditions are submitted to the computer for mathematical "decoding". The computer output is plotted as Load-Displacement diagrams at the surface, at desired points in the rod string (i.e. junctions in tapered strings) and at the pump (similar to the

Gilbert[4] pump dynagraph). The loading information at junction points is extremely useful in analyzing sucker rod failures. Table I summarizes the various criteria evaluated by the computer technique and emphasizes the advantages it has over visual interpretation of a mechanical dynamometer card.

The computerized analytical technique affords a complete evaluation of down-hole pumping conditions with significant advantages over a mechanical (surface) dynamometer.

EVALUATE	Mechanical Dynamometer	Computer Technique
Surface Loads & Stresses	Yes	Yes
Torsional Analysis	Yes	Yes
Pump Dynagraph	No	Yes
Maximum Plunger Stroke	No	Yes
Effective Plunger Stroke	No	Yes
Pump Displacement	No	Yes
Pump Efficiency	No	Yes
Plunger Slippage	No	Yes
Traveling Valve Leak	Possible	Yes
Standing Valve Leak	Possible	Yes
Gas Interference	Possible	Yes
Fluid Pound	Possible	Yes
Pump Intake Pressure	No	Yes
Loads & Stresses - Tapered Rod String	No	Yes
Tubing Movement	No	Yes
Tubing Anchor Malfunction	No	Yes
Packer Malfunction	No	Yes

TABLE 1



TYPICAL POLISHED ROD AND DISPLACEMENT HISTORIES

FIGURE 1

INTERPRETATION OF PUMPING CARDS

How many wells have been fraced or acidized needlessly, when a simple pump change-out or gas-anchor redesign would have sufficed? How many wells have had numerous pump change-outs and other down-hole equipment modifications, when the inflow of the oil had been hampered by skin-effect or wellbore damage, that actually required down-hole treatment?

In securing satisfactory operation of a pumping well, it would seem desirable to distinguish clearly between the performance of the pumping equipment and the performance of the well itself, considering the well performance with regard to both individual possibilities and to the part the well should play in the general scheme of economic withdrawal of oil and gas from a given producing zone.

Pumping Equipment - Performance

Perfect Pump Card—Tubing Anchored: Using the computer technique pump performance is shown graphically as a load-displacement diagram or pump card. Fig. 2(a) illustrates perfect mechanical pump performance, with no tubing movement and only liquid being handled. The distance between A-D and B-C is the fluid load (W) being lifted by the plunger. The negative load from the zero load line to the line A-D, ideally, indicates the bouyant forces (B) of well fluid on the rod string. These bouyant forces are the resultant **compressive** forces acting on the lower portion of the rod string but they **do not** cause the rods to buckle, as was shown by Okon[5] in 1964. The distance B-C, is the intake stroke of the plunger; D-A is the discharge stroke; in this example both are equal. The successive steps in such a pump operation are as follows: (1) at the start of the upstroke (Point A), traveling valve closes; (2) from A to B, the fluid load is transferred to rod string as gas in clearance space (if present) expands from static tubing pressure (P) to pump intake pressure (PIP); (3) standing valve opens at B, allowing fluid to enter pump chamber when pressure drops below intake pressure (PIP); (4) from B to C, fluid load is carried by rods as fluid is drawn into pump; (5) at C, standing valve closes as plunger starts down, traveling valve remains closed; (6) from C to D, gas in the pump (if present) is compressed and fluid load is transferred from rods to tubing; (7) at D, pump discharge pressure (Pd) equals static tubing pressure (Pt), and traveling valve opens; (8) from D to A, fluid is displaced through traveling valve into tubing.

All of the pump cards discussed in this paper will follow the same general operating cycle, modified only by various mechanical malfunctions (leaky valves, faulty tubing anchor, etc.) or physical characteristics of the well (low PIP, gas interference, etc.).

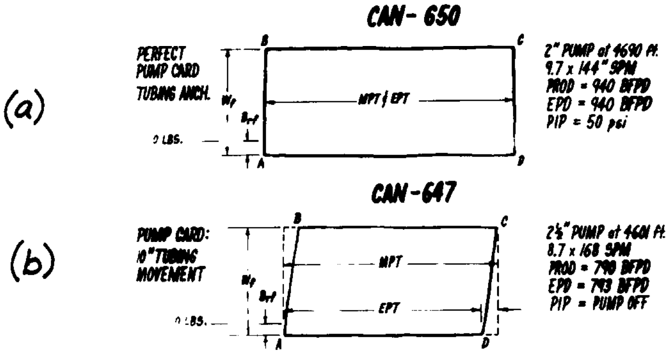


FIGURE 2

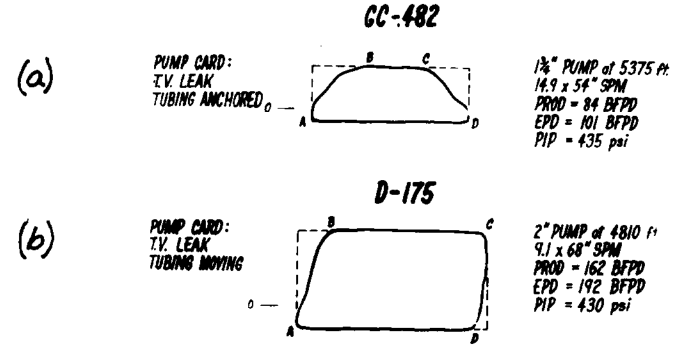


FIGURE 3

Detection of Tubing Movement: A special feature of the computer technique permits sensing of tubing movement. The movement of tubing affects the manner in which the fluid load is transferred to and from the rod string. The parallelogram shape of Fig. 2(b) is caused by the stretching and contracting of the unanchored tubing during the transfer of fluid load to and from the tubing. It should be noted that unanchored tubing vibrates as an elastic body because of the intermittent application of the fluid load. Thus, in some cases the segments during load pickup (A to B) and release (C to D) are not as straight and clear-cut as the example in Fig. 2(b).

In wells having effective tubing anchors, such as Fig. 2(a), the tubing movement is restrained and the resulting pump card will be rectangular in shape, provided, of course, that the pump is functioning properly and pumping only liquid.

This particular aspect of the computer program is especially useful in detecting a malfunctioning tubing anchor or packer, as will be illustrated later.

Leaking Pump Valves: Leaking traveling valves or excessive plunger slippage cause a delay in picking up the fluid load, Fig. 3(a), from A to B and a premature unloading from C to D (the standing valve closes during the upstroke). It is generally accepted that all pumps leak to a certain extent, but when the leak is of sufficient magnitude to arch the top of the pump card, remedial action is warranted.

Where the tubing is unanchored, the parallelogram shape of the unanchored-tubing card is superimposed on the arched-top of the leaky T.V.-pump card to yield a card with different slopes on the ends as shown in Fig. 3(b). This is caused by the effects of the tubing contraction and the leaky T.V. being additive from A to B, and the leaky T.V. effect and the tubing stretch effect essentially cancelling out from C-D, because of their opposed slopes.

The card for a leaky standing valve would have an arched-bottom, similar to turning Fig. 3(a) upside-down, because the pump is quick to pick up the load but slow to release.

Well Performance

Pump Intake Pressure: The determination of individual well characteristics is a matter of prime importance, and there can be no doubt as to the significance of determining fluid levels in relation to rates of inflow in securing efficient operating of pumping wells.

One method of estimating intake pressure is provided by the computer technique. This method is not hampered by electrical cable troubles, annular space limitations, or packers in the well. Though it is not extremely precise, the method has been used extensively to obtain adequate engineering estimates of pump intake pressures (PIP).

The method of determining the pump intake pressure has been discussed by both Gibbs and Neely[1], and Eichmeier[2]. Interested readers should consult these papers.

Fluid Pound: Fluid pound on a pump card is generally evidenced by a "pan-handle" shaped card as illustrated in Fig. 4(a). The pump components in this well are functioning properly and the tubing is firmly anchored.

With unanchored tubing, the shape again resembles a parallelogram but with a "handle" on the right end. In the example Fig. 4(b), the "handle" is extremely short, as it should be

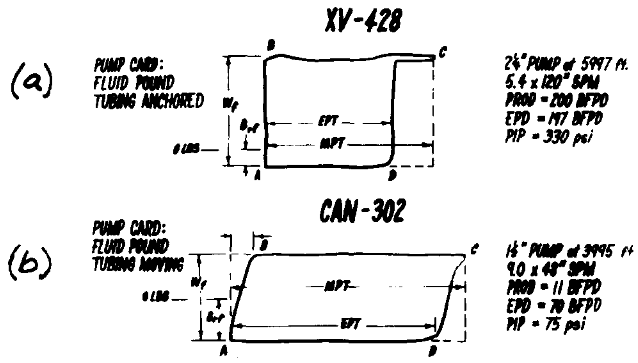


FIGURE 4

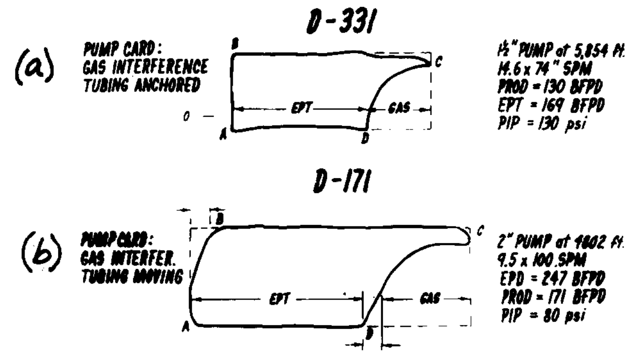


FIGURE 5

under ideal pumping conditions. The longer the fluid load is carried by the rods on the downstroke (up to some intermediate point) the greater the plunger velocity and the greater the shock load on the rods.

It is interesting to note that the PIP of Fig. 4(a) is 330 psi. The pounding is not caused by excessive pump displacement (as is usually the case in wells pounding fluid) but rather, an instance where the operator is pumping highly viscous oil (8° API gravity, asphalt base) with too small a standing valve opening.

Gas Interference: The use of the computer technique has proved conclusively that loss of pump displacement in wells at pumping depths below 5000 ft is generally not the result of stroke loss due to rod stretch, but may often be attributed to ineffective separation of gas from the liquid pumped.

An oilwell pump is designed primarily to lift oil to the surface, although in many cases it is required to handle some gas in the free state. Unfortunately, a sucker rod pump (or any other type of mechanical lifting device) is a relatively poor gas compressor. Therefore, it is essential to minimize the amount of free gas which the pump must handle. It is desirable, then, to know the severity of any down-hole gas separation problems that may exist. The shape of the pump card will certainly pinpoint such problems.

It can be seen in Fig. 5(a) that the pump cycle generally follows that described above in discussing Fig. 2(a). The main difference is that from Point C to Point D the rod-to-tubing unloading is affected by the gas in the pump and follows a gas compression curve. Effective plunger stroke is shortened by the gas interference.

It can be seen in Fig. 5(a) that detecting tubing movement becomes less clear-cut in wells which have considerable free gas. The expansion and compression of the gas in the pump could be confused with tubing movement. The interpretation problem is not insurmountable. Good pump spacing, such as evidenced in Fig. 5(a) (the square corner at Point B), minimizes gas expansion effects during load pickup. In Fig. 5(b) notice the slope change as the load pickup approaches Point B. The steeper slope is the rod-to-tubing transfer line, and the slope diminishing continuously towards the horizontal at Point B is caused by gas expansion and is the result of poor pump spacing—reducing the compression ratio of the pump.

In both of these examples the PIP is less than 150 psi; however, a gas interference or gas-locked condition is no guarantee that the well is pumped-off. With gas interference the percentage volumes of gas and liquid in the pump are constantly changing; and for this reason the operating compression ratio of the pump tends to limit the extent to which the fluid level may be lowered.

The importance of excluding gas from the pump cannot be over-emphasized. A vast majority of both surface failures and down-hole problems are initiated by ineffective separation of the oil and gas downhole.

Gas or Fluid Pound?: For years it has been assumed that it was possible to distinguish between a gas pound and a fluid pound by visual analysis of a polished rod card, the criteria being that gas interference would manifest itself on the downstroke as a compression curve; and that fluid pound would be evidenced by a sudden unloading of the rods, introducing severe shock waves into the system. But this is not always true.

By examining and comparing the surface cards of the fluid pound example (Fig. 6) and the gas interference card of (Fig. 7), it can be seen that the unloading of the rods is faster and shock waves of greater intensity are set up with the gas pound than with the fluid pound. Only by observing the computer derived pump cards is the gas or fluid pound question resolved beyond doubt, making better and more effective operations possible.

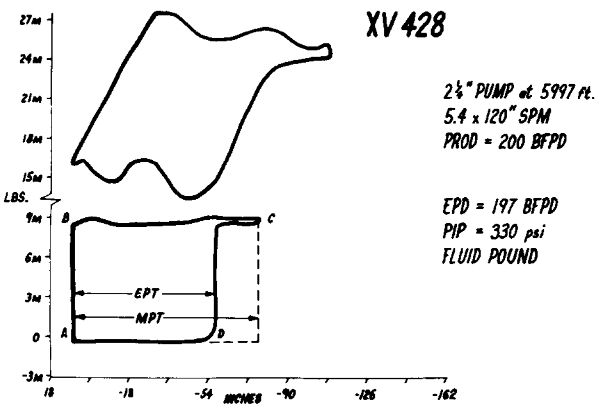


FIGURE 6

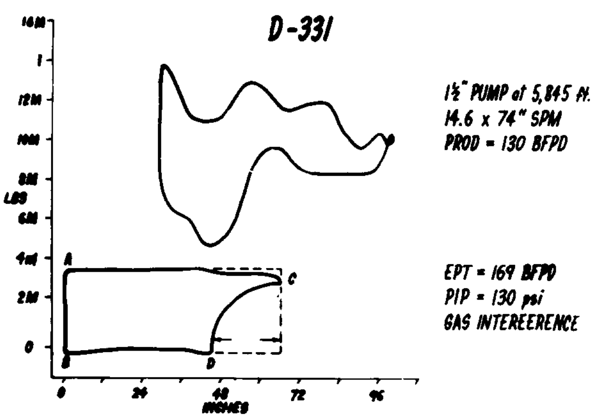


FIGURE 7

ROD STRESSES AT INTERMEDIATE DEPTHS

Historically, the design of tapered rod strings has been based on equating maximum stress at the top of each section in the taper. This maximum stress is calculated considering only static load conditions. No consideration has been given to dynamic loading or stress ranges occurring at the top of each taper. By requesting a load-readout at any desired depth in the rod string (usually at junction points), the computer technique can be used to analyze loading conditions, where severe rod loading is suspected and where the frequency of rod failures is high.

API Modified Goodman Diagram

The most expedient means of evaluating the rod loading is to apply the maximum and minimum rod stresses at the junction points to the API Modified Goodman diagram.[6]

Referring again to Fig. 6, this well has a four-way taper: 1525 ft of 1-1/8 in., 1675 ft of 1-in., 1925 ft of 7/8-in., and 825 ft of 3/4-in. rods. The load-readout from the computer was as follows:

TABLE II

Top Rod (in.)	**Depth (ft)**	**Stress (psi) Maximum**	**Stress (psi) Minimum**
1 1/8	0	27,600	13,850
1	1,525	27,100	11,100
7/8	3,200	26,400	7,450
3/4	5,125	23,500	2,190

Fig. 8 illustrates the stresses graphically on an API Modified Goodman Diagram. While the maximum stresses in the tapers are not well balanced, it can be seen that as these stresses increase, the range diminishes and that none of the minimum stresses fall below the minimum allowable stress line into the excessive stress range area.

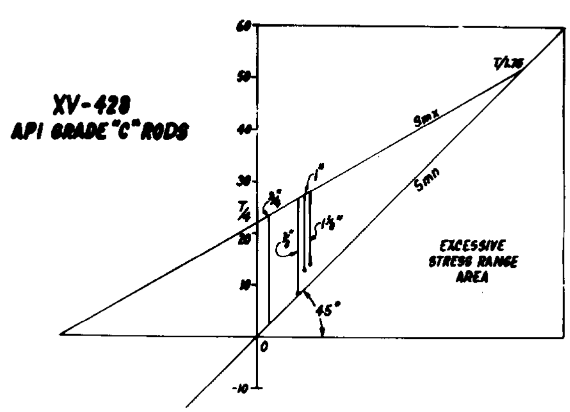


FIGURE 8

Unfortunately, this was not the case with the well shown in Fig. 7 which had a double taper of: 2200 ft of 3/4-in. and 3600 ft of 5/8-in. rods. The load-readout for the junctions are plotted on the Goodman Diagram of Fig. 9. The top 3/4-in. rod at the surface had a maximum stress of 30,900 psi and a minimum stress of 10,150 psi. The top 5/8-in. rod at 2200 ft had a maximum stress of 27,800 psi and a minimum of 5050 psi. Both top rods had minimum stresses below the minimum allowable and fell in the area of excessive stress range. This type of loading will cause premature fatigue failures in the upper sections of both tapers. In this particular well the extreme range of loading was caused by the gas pound and could be alleviated by minimizing the gas interference.

CASE HISTORIES

The next few pump cards and surface cards to be examined were taken from some 700 well surveys run in the last two years throughout the United States, Canada and Venezuela. They represent just a few of the conditions which can be detected using the computer technique.

Case RM 333-2

The pump card from RM333-2 (Fig. 10) is an example of a pump with excessive plunger slippage, as evidenced by the diminishing fluid load line during the upper two-thirds of the upstroke. The comparison of the 558 BFPD produced with the effective plunger displacement (EPD) of 632 BFPD verified that some 80 BFPD was being "lost" between the discharge stroke and the stock tank. The tubing was unanchored and moving 11 in. which resulted in an equal loss of plunger stroke. The PIP of 410 psi, plus the shape of the pump card indicated that more fluid could be produced. However, the pump

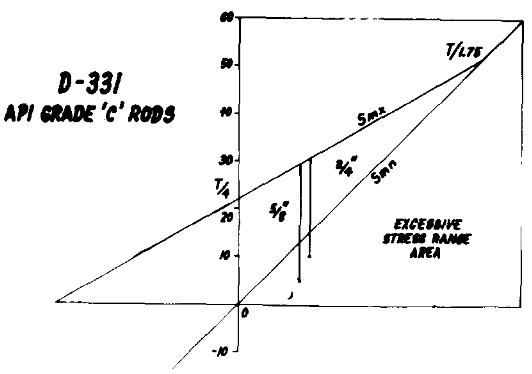


FIGURE 9

unit, a 320-256-120 was being operated with 627,000 in.-lbs of peak torque.

The operator moved in a larger pumping unit, anchored the tubing, is pumping a 2-1/4 in. pump at 5333 ft, 9.5 x 168" SPM and has INCREASED THE OIL PRODUCTION BY 191 BPD.

Case RM 339

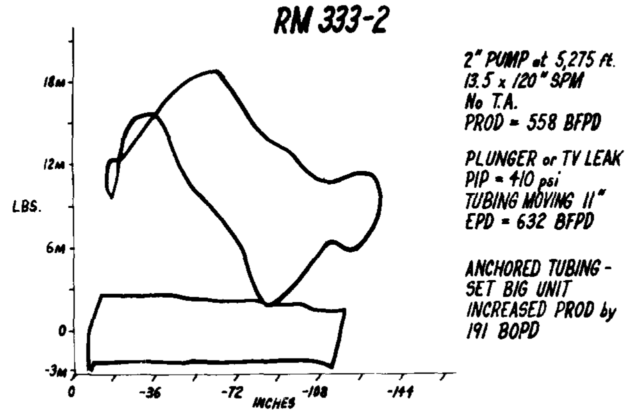


FIGURE 10

This survey was run as one of a five-well project in April 1966. Three of the five were "problem" wells—a high frequency of rod failures in all three wells; the other two "control" wells were similar in depth, production, pumping cycle, etc. to the problem wells but were experiencing no rod problems.

The computer technique was used to analyze and alleviate the rod breaks in the three problem wells but the most significant finding was in one of the "control" wells—RM 339 (Fig. 11). The tension-type tubing anchor was set with insufficient tension and was moving up and down 12 in. with each stroke, some 12,600 times a day!

The operator attempted unsuccessfully to reset the tubing anchor; it was pulled and the slips were found to be worn smooth. Fortunately, through the use of the computer technique, the moving tubing anchor was found before it had worn through the casing, which would have resulted in an expensive milling job and casing squeeze.

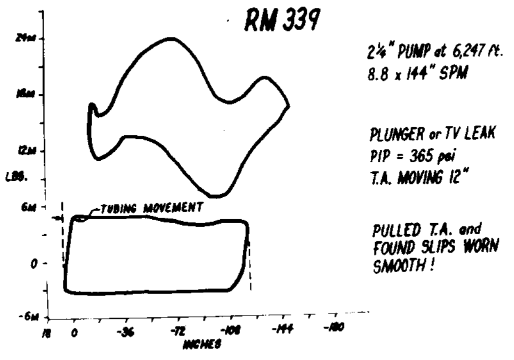


FIGURE 11

Case XV 450

The problem set forth by the operator of this well was to increase his production. From the shape of the pump card (Fig. 12), the well is hampered by gas interference; however the computed PIP showed the well to be pumped off at this depth. In order to obtain more production, the pump must be lowered and the gas must be excluded from the pump. The diminishing fluid load line on the upstroke is indicative of a worn plunger or traveling valve; however, the difference of some 670 BFPD between the production test (774 BFPD) and the EPD (1447 BFPD) was too great to attribute to the worn pump. Uphole leakage was suspected. Tubing movement was losing 14 in. of effective plunger stroke.

The operator pulled the pump, tested his tubing and found four collar leaks in the lower tubing (caused by the unanchored tubing rubbing against the casing). The new pump was lowered to 4000 ft, care being taken to space

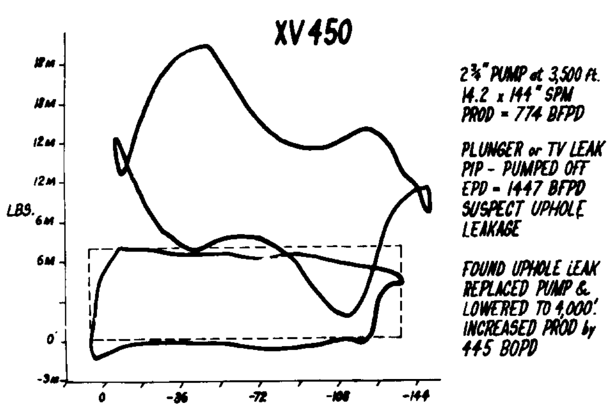


FIGURE 12

it properly for maximum compression. This resulted in an INCREASE IN OIL PRODUCTION of 445 BPD.

SUMMARY

While the "possibles" listed in Table I depend on the skill and experience of the mechanical dynamometer operator, the computer technique, using a mathematical analysis, virtually eliminates the human elements (skill, experience, and **error**) and transforms the "art" of dynamometer interpretation into a science.

A useful analogy of the two techniques is to think of the mechanical dynamometer as a stethoscope and the computer analysis as an Electrocardiogram (EKG). The stethoscope is still a valuable tool in medicine but admittedly, it has its limitations as a diagnostic tool. The EKG can give the doctor more complete and quantitative information for the proper diagnosis.

Similarly, the mechanical dynamometer is still a valuable tool for evaluating loads and stresses on the surface equipment but it does have its limitations as a diagnostic tool.

The analytical computer technique affords an "in-depth" evaluation of sucker rod pumping installations, with a complete picture of the work the pump (or "heart" of the system) is performing, as well as the loads and stresses throughout the rod string and on the surface equipment.

With the cost-price squeeze prevailing throughout the oil industry, the oil operator is wondering—"Where can I look to reduce costs and improve the profit picture? Can I improve the efficiency of well productivities and increase production? Where do I look to halt rising lifting costs?" The significant advances in diagnostic analysis offered by the computer technique could provide the answers to those questions.

With a greater understanding of all aspects of sucker rod pumping, as obtainable through the use of this technique, it is inevitable that further significant advances in the technology of rod pumping will be forthcoming.

REFERENCES

1. Gibbs, S. G. and Neely, A. B., "Computer Diagnosis of Downhole Conditions in Sucker Rod Pumping Wells", SPE Paper No. 1165, Journal of Petroleum Technology, Jan. 1966.

2. Eichmeier, J. R. "Applications of the Delta II Dynamometer Technique", **The Journal of Canadian Petroleum Technology,** April-June, 1966. Also published as "Diagnostic Analysis of Dynamometer Cards", **Journal of Petroleum Technology,** Jan, 1967.

3. Herbert, W. F., "Sucker-Rod Pumps Now Analyzed with Digital Computer", **Oil and Gas Journal,** Feb 21, 1966.

4. Gilbert, W. E., "An Oilwell Pump Dynagraph", **Drilling and Production Practices,** API 1936.

5. Okon, U. I., "The Effect of Bouyancy on Drill Pipe", thesis in petroleum engineering, University of Oklahoma 1964.

6. API Std 11B, Appendix A, March 1966.

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