SYSTEMS ANALYSIS APPLIED TO ROD PUMPED WELLS

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ABSTRACT

System analysis methods are widely used to describe the performance of flowing and gas lifted oil wells and several applications deal also with gas wells. The present author's aim is to apply these procedures to sucker rod pumping and to develop calculation methods for modeling the operation of rod pumped wells.

A discussion of systems analysis methodology is given first. Then, a sucker rod pumped well is analyzed and considerations are given on the application of these methods to describe the performance of a pumping system. Calculation methods are developed for the case of a conventional geometry pumping unit pumping liquid only. The behavior of the pumping system is described by System Performance Curves which are plots of production rate vs. pump setting depth for different pumping modes. These curves enable the evaluation of different pumping units and different rod materials under the same conditions. The interaction of the well inflow performance and the production capacity of the pumping system is easily analyzed with the utilization of System Performance Curve sheets. This is accomplished by superimposing the well's IPR curve on the sheet and by reading off the production rates valid at the intersections of the IPR and the System Performance Curves.

The developed analysis method is illustrated by example problems. It is shown that the use of the proposed curves provides an efficient means to analyze the performance of sucker rod pumping systems.

INTRODUCTION

Petroleum fluids found in an underground reservoir must be moved through a complex system to reach their destinations on the surface. This system is called the production system and comprises the following main components: the reservoir, the producing well, the surface flowline, and the separator. Some of these can further be divided into smaller elements, e.g. the well, besides the tubing string, may contain safety and/or gas lift valves, etc. The production system is thus a system of interconnected and interacting elements which all have their own specific performance relationships but each, in turn, also depends upon and influences the other elements. In order to produce fluids from the well all components of the system must work together. Thus the solution of any fluid production problem requires that the production system be treated as a complete entity.

The outlines of the above principle were first given by Gilbert [1], the father of production engineering, in the 50's. He described the interaction of the reservoir, the well, and the wellhead choke and proposed a system-oriented solution for determining the production rate of a flowing well. The practical use of Gilbert's ideas was limited due to the limitations of the methods available in his time for modeling the performance of the system's elements. During the last decades, however, research into the behavior of the individual hydraulic elements of oil and gas wells has been very intensive. As a result of this progress, there exist today several different theories, calculation, and design procedures that reliably model the performance of a production system's elements. Good examples for this are the numerous correlations available for calculating pressure traverses in vertical and horizontal pipes, etc.

The wide selection of available calculation models and the advent of computers that eased the burden of the necessary calculations have lead to the reappearance of Gilbert's ideas in the early 80's [2,3]. The new contributions aim at the numerical simulation of the production system and enable one to optimize the production of the desired flow rate. Although most of the investigators study the production system only, the basic concepts are already laid by Szilas [4] for the integration of these achievements into the description of a whole field's behavior.

The systems analysis methods and procedures mentioned above were named "Nodal Analysis" by K.E.Brown which term has generally been accepted. A full treatment of nodal analysis principles is given in [5,6]. The application of this theory to flowing and gas lifted wells can have immediate practical and economical advantages [7,8].

DESCRIPTION OF THE PRODUCTION SYSTEM

Consider a simple flowing oil well the schematic drawing of which is shown in **Fig. 1**. Fluids in the formation flow to the well from as far as the boundary of the drainage area, **1**. After entering the well through the sandface, vertical flow in the tubing starts at the well bottom, **2**. The tubing string may contain a safety valve and/or a downhole regulator, represented by **3**. Downstream of the restriction, vertical tubing flow takes place up to the wellhead, **4**. A surface choke bean is installed at **5**, which is also the intake point to the flowline. Horizontal or inclined flow in the flowline leads into the separator, **6**.

The points in the flowing well's production system designated by numbers in **Fig. 1** constitute the nodes of the nodal analysis theory. They separate the different components of the system: the formation, the tubing string, the flowline, etc. In order to define the system's behavior all components must first be evaluated separately, these evaluations forming the base of the total system's description.

Any oil or gas well's production system can be divided into its components using appropriately placed nodes. A typical sucker rod pumped case is illustrated in **Fig. 2.** The unique features of a common rod pumped well are the absence of a packer in the well and the connection of the annulus at the casing head to the flowline, usually through a check valve. Due to the annular space being open both downhole and at the wellhead, two paths are available for the fluids to move up the hole. One of these is the tubing string where fluids are lifted to the surface by the downhole pump. The other path open to fluids is in the annulus where liquids rise to a stationary level, above which a gas column exists. Since the two flow paths are connected at the bottom (Node 2 in **Fig. 2**), it follows from the hydrostatic law of communicating vessels that the pressures exerted at Node 2 by each subsystem must be equal. The result of this requirement is that, in contrary to flowing wells, there are two ways to calculate bottomhole pressures in pumping wells: one through the tubing string and the other in the annulus. The dynamic liquid level, therefore, is an indicator of the well's actual bottomhole pressure. This observation is of great importance to the systems analysis of rod pumped wells, as will be seen later.

THE BASICS OF SYSTEMS ANALYSIS

One of the main objectives of nodal systems analysis is the determination of the flow rate of a given production system. As discussed before, in connection with **Fig. 1**, an oil well can be considered a series-connected hydraulic system made up of its components which are bracketed by appropriately placed nodes. Evaluation of this system's performance permits the following conclusions to be drawn:

- The mass flow rate throughout the system is constant, although phase conditions change with changes in pressure and temperature.
- Pressure decreases in the direction of flow because of the energy losses occurring in the various system components.
- At node points, input pressure to the next component must equal the output pressure of the previous component.
- System parameters being constant for considerable periods of time are:
    - the endpoint pressures at the separator and in the reservoir,
    - wellbore and surface geometry data (pipe diameters, lengths, etc.), and
    - inflowing fluid composition.

Taking into account the above specific features of the production system a procedure can be devised to find the flow rate at which the system will produce. This starts with dividing the system into two subsystems at an appropriately selected node. The next step is to find pressure vs. rate curves for each subsystem. These functions are constructed starting from the known points in the system at the separator and at the well bottom. The common point of the two curves gives the cooperation of the subsystems and thus the desired rate.

SYSTEMS ANALYSIS OF PUMPING WELLS

A schematic drawing of a pumping well, showing the different components of the production system along with the various nodes separating them is shown in **Fig. 2**. Systems analysis principles have shown that the production equipment and the formation are connected in series at the well bottom. This implies that the same liquid rate must flow through both components of the system. Therefore, in order to find the production rate under some specific conditions, a common solution of the performance of the two components must be sought. Since liquid inflow from the formation is characterized by the familiar IPR equation, only the performance of the pumping system has to be described. This involves the determination of a pumping rate - bottomhole pressure relationship, which can be superimposed on the IPR curve to find the total system's production rate.

As seen from **Fig. 2**, two paths are available to describe the pumping system's performance: one in the tubing and the other in the casing annulus. In the first case, methods developed for flowing or gas lifted wells can be applied, but this approach necessitates the calculation of two-phase pressure drops in the tubing - rod string annulus with increased calculation requirements and reduced accuracy. The work of Schmidt and Doty [9] followed this line of thought. One of the few other publications on systems analysis of pumping systems is contained in Kermit Brown's book on artificial lifting [5]. The methods presented in that book utilized formulae of limited validity and were only given, as the authors stated, "... to encourage others to continue the work ...".

The procedure developed in this paper, in contrary to previous investigations, is based on modeling the phenomena occurring in the well's annulus. It is well known that the depth of the dynamic liquid level is a direct indication of the well's flowing bottomhole pressure. This fact is utilized in the calculation procedure and the concept of System Performance Curves for describing the operation of the pumping system is introduced.

System Performance Curves

To describe the performance of a rod pumping system, the pumping rates attainable at different conditions have to be found. The conditions having the most significant impact on the production rate are:

- The pumping mode used, i.e. the combination of pump size, polished rod stroke length, pumping speed, and rod string design.
- The pump setting depth.

In the light of the above, the performance of the pumping system can effectively be described by plotting pumping rates versus pump setting depth for different pumping modes. These plots are defined here as System Performance Curves and can be constructed by utilizing any calculation procedure that properly approximates the operational parameters of pumping. The curves thus created represent the rates attainable with different pumping modes from different depths and show the performance of the pumping system alone. In the following, System Performance Curves are developed with the basic assumptions listed below:

- Conventional pumping units are considered, allowing for RP 11L [10] procedures to be used.
- Pumping of a single-phase liquid is assumed and the effects of any free gas in the annulus are disregarded.
- Pumped-off conditions are presumed with the dynamic liquid level being at pump setting depth.

Although the above restrictions can considerably affect the applicability of the analysis method, there are several conditions where these requirements are met, e.g. wells produced from a strong water-drive reservoir.

The procedure to construct System Performance Curves is illustrated on the flowchart shown in **Fig. 3**. After the input of the necessary basic data, the parameters of a pumping mode are input: plunger size, d, polished rod stroke length, S, and pumping speed, N. A value for pump setting depth, L, is assumed and the RP 11L calculations are used to find the operational parameters of pumping at the given conditions. The most important of these is pump displacement rate, PD, which, if plotted in the function of setting depth, L, gives one point on the System Performance Curve. Next, the calculated operating parameters are checked for overload conditions by evaluating the loading on the rods and on the pumping unit. In case the fatigue limit of the rods is exceeded, or either the unit structure or the speed reducer is overloaded, the maximum attainable pump setting depth has been reached and a new pumping mode is processed. In all other cases the pump setting depth, L, is increased and calculations are repeated with the new depth. After a prescribed maximum depth, L_{max}, is reached, another pumping mode is selected and the whole procedure is repeated. The described method yields several corresponding pumping rate - setting depth points for every assumed pumping mode which define the System Performance Curves.

Figs. 4 and **5** show example System Performance Curves for a pump diameter of 1.25" and for API tapers of 76 and 86, respectively. Further, an anchored tubing string, 100% pump volumetric efficiency and pumping of water were assumed. Each sheet contains calculated pumping rates plotted against pump setting depth for selected polished rod stroke lengths and pumping speeds. Pump size, API taper number, and rod material are held constant on every sheet. The different curves on such sheets, therefore, represent different pumping modes.

Every performance curve starts, at a pump setting depth of zero, from the pumping rate that could be calculated with a plunger stroke length equal to polished rod stroke length. As pump setting depth increases, a point is reached where maximum rod stress, due to the combined effects of fluid load, rod string weight, and dynamic forces exceeds the allowable stress for the rod material. This depth gives the maximum pump setting depth that can be reached with the given rod material (Grade D in the examples). Comparison of **Figs. 4** and **5** shows that the use of a stronger (86 taper) string instead of a 76 taper allows pumping from greater depths. But this holds only if rod strength is considered to be the sole limiting factor.

In order to properly describe the system's performance, the operational characteristics of the surface equipment must also be taken into account. Therefore, the structural capacity of the pumping unit, as well as the allowable torque rating of the speed reducer must not be exceeded by the actual peak polished rod load and the peak torque, respectively. These effects are considered in **Figs. 6** and **7**, valid for a C-228D-213-100 pumping unit. Compared to the previous figures, the individual curves end at smaller depths than rod strength alone would allow. This is caused by the fact that the mechanical limitations of the pumping unit (maximum structural load or maximum allowed gearbox torque) are reached before the rod string is overloaded. As can be seen, the use of the heavier string with the API 86 taper overloads the pumping unit at much less depths than the API 76 string. Thus, in contrary to the conclusions drawn from **Figs. 4** and **5**, the lighter rod string can be operated at greater depths than the heavier one. **Fig. 8** shows similar curves for a 2" plunger and an API 76 taper string.

The Use of Performance Curves

After the performance of the lifting equipment has been determined, the operation of the other system, i.e. the productive formation must be described. It can be shown that inflow performance (IPR) curves plot as straight lines in the coordinate system production rate vs. dynamic liquid level, used for displaying System Performance Curves. Systems analysis, therefore, can be accomplished by superimposing the IPR of the well on the System Performance Curve sheet valid for the given conditions. Intersections of these curves give pumping rates attainable under different conditions and allow the determination of the various possible common operating points of the formation and the rod pumping system.

To illustrate the procedure, an example well with a productivity index of PI = 0.46 bpd/psi, and the following data was used to construct straight-line IPR curves in **Figs. 6 - 8**:

- Well depth = 3,000 ft
- Static liquid level = 1,000 ft
- Dynamic liquid level at 400 bpd liquid production = 3,000 ft.

The intersections of the IPR line with the System Performance Curves indicate, for different pumping modes, the rates attainable, along with the corresponding pump setting depths required to achieve those rates. Provided that System Performance Curve sheets for different pumping units are available, one has only to select the right sheet and to plot the actual IPR on it, in order to analyze the performance of different pumping systems. Therefore, the above method can be utilized for designing a sucker rod pumping system with due regard to well deliverability and to ensure an efficient pumping operation. The use of this procedure, however, is limited by the basic assumptions indicated earlier, and for cases when sufficient information on well inflow performance is available.

EXAMPLE PROBLEM

Find the pumping rates for the available pumping modes indicated in **Figs. 6** and **8**. Determine the maximum rate which can be achieved from the well, if available plunger sizes are 1.25" and 2", and an API 76 taper rod string is used.

Table 1 contains pumping rates read off from **Figs. 6** and **8**, at the intersection of the IPR and System Performance Curves.

The maximum rate is found as 370 bpd with the following pumping mode: 2" plunger, 86" stroke length, 10 strokes/minute pumping speed. The dynamic fluid level is at 2,780 ft in this case, showing nearly pumped-off conditions to prevail.

CONCLUSIONS

1. A calculation procedure is proposed for the systems analysis of rod pumped wells producing gas-less liquids.
2. The concept of System Performance Curve is introduced to model the operation of a conventional rod pumping system.
3. System Performance Curve sheets, constructed for different pumping units and operational conditions, can provide an easy-to-use means to analyze the performance of the pumping system in any well.

ACKNOWLEDGMENT

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REFERENCES

1 Gilbert, W.E.: "Flowing and Gas-lift Well Performance." API Drilling and Production Practice (1954) 126-57

2 Proano, E.A. - Mach, J.M. - Brown, K.E.: "Systems Analysis as Applied to Producing Wells." Congreso Panamericano de Ingeniera del Petroleo. March 1979 Mexico City

3 Mach, J.M. - Proano, E.A. - Brown, K.E.: "A Nodal Approach for Applying Systems Analysis to the Flowing and Artificial Oil and Gas Wells." SPE 8025

4 Szilas, A.P.: "Field-Integrated Production System Cuts Costs." OGJ June 13 (1983) 125-8

5 Brown, K.E.: "The Technology of Artificial Lift Methods." Vol.4 PennWell Publ. Co. (1984)

6 Brown, K.E. - Lea, J.F.: "Nodal Systems Analysis of Oil and Gas Wells." JPT Oct. 1985 1751-63

7 Mach, J.M.: "Apply Nodal Analysis to Production Systems." Well Servicing Vol. 21 No. 1 (1981)

8 Kanu, E.P.: "Systems Analysis Hikes Well Performance." PEI May 1981 96-119

9 Schmidt, Z. - Doty, D.R.: "System Analysis for Sucker Rod Pumping." SPEPE May 1989 125-30

10 "Recommended Practice for Design Calculations for Sucker Rod Pumping Systems (Conventional Units)." **API RP 11L** 4th Ed. (1988)

Table 1
Pumping Rates Read Off from System Performance Curves for the Example Conditions

Stroke Length	Pumping Speed	Pumping Rate, bpd for Plunger Size	
in	1/min	1.25"	2"
73	4	52	130
	10	130	310
	16	210	-
86	4	65	150
	10	155	370
	16	245	-
100	4	75	180
	10	180	-
	16	290	-

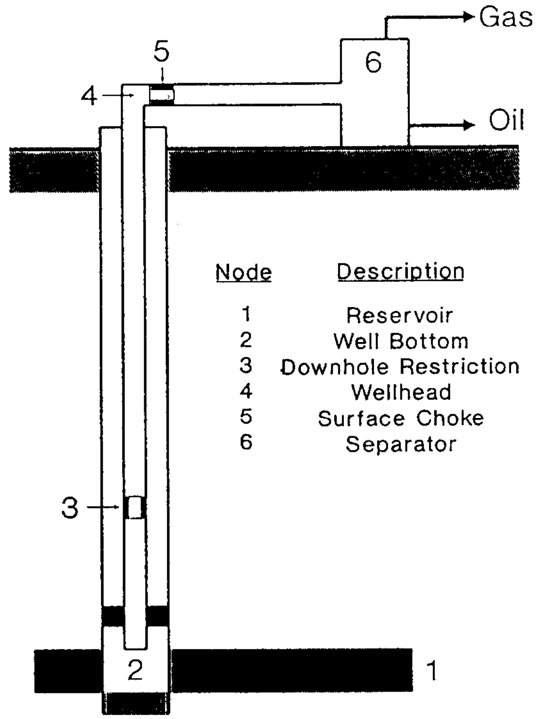

Figure 1 - The production system of a flowing well

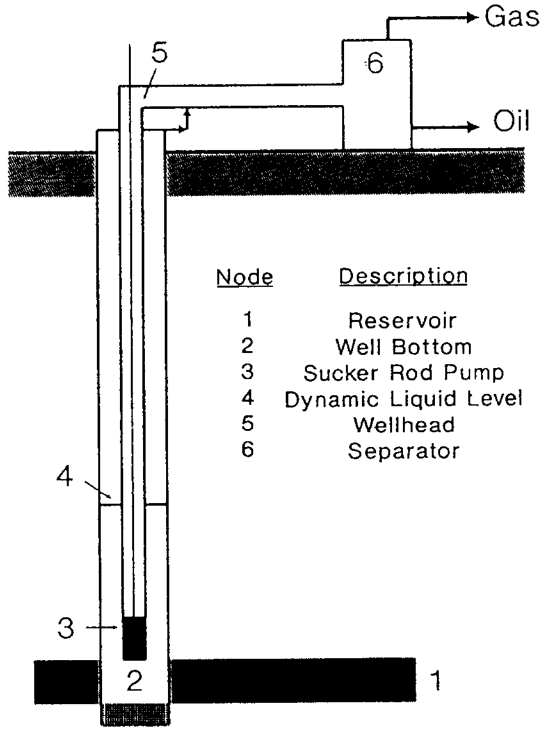

Figure 2 - The production system of a rod pumped well

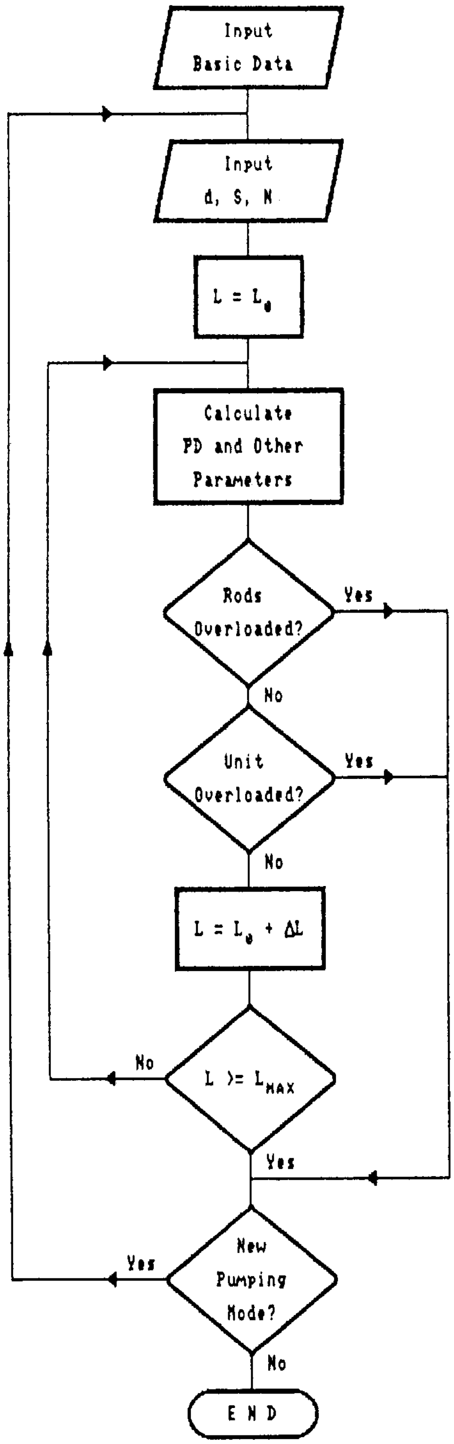

Figure 3 - Flowchart of the procedure to construct System Performance Curves

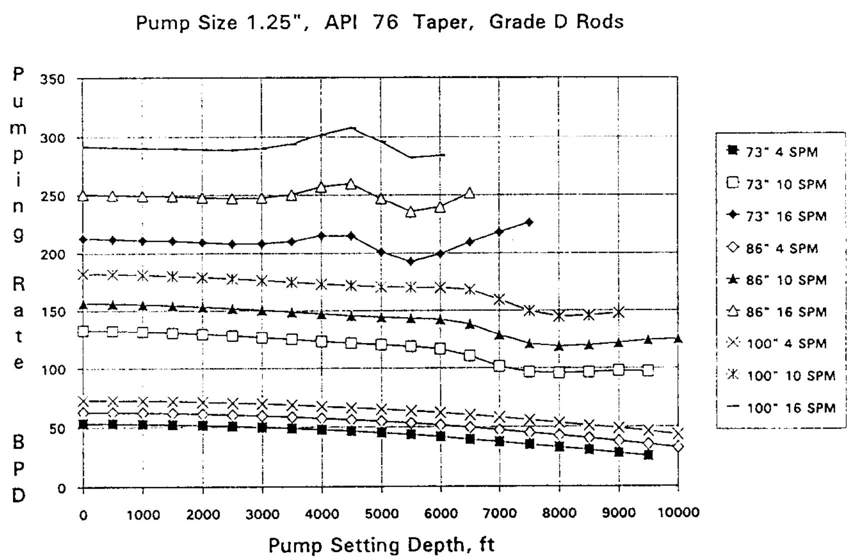

Figure 4 - System Performance Curve sheet for a 1.25" plunger, API 76 taper rod string, and Grade D rods

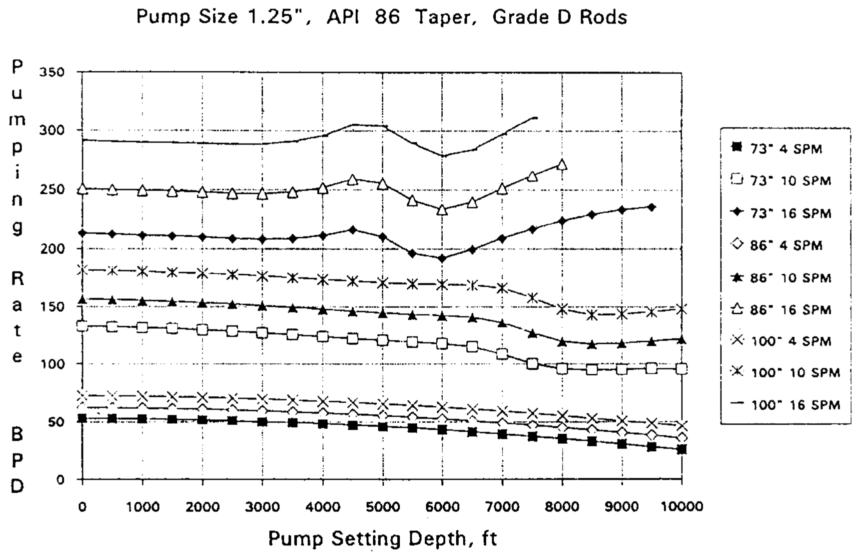

Figure 5 - System Performance Curve sheet for a 1.25" plunger, API 86 taper rod string, and Grade D rods

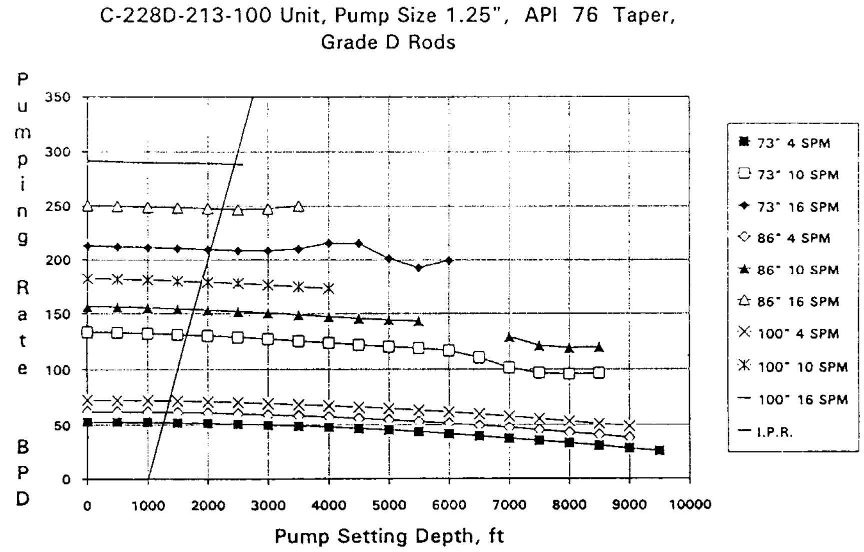

Figure 6 - System Performance Curve sheet for a C-228D-213-100 unit, 1.25" plunger, API 76 taper rod string, and Grade D rods

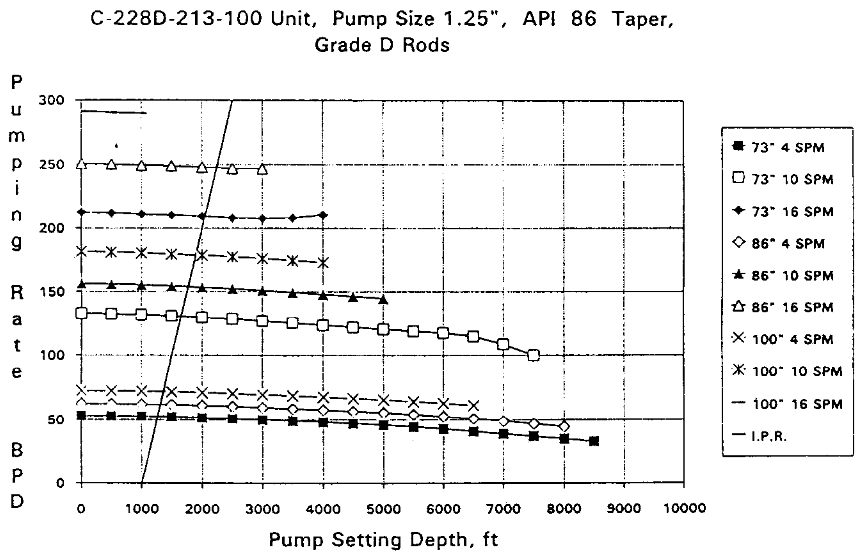

Figure 7 - System Performance Curve sheet for a C-228D-213-100 unit, 1.25" plunger, API 86 taper rod string, and Grade D rods

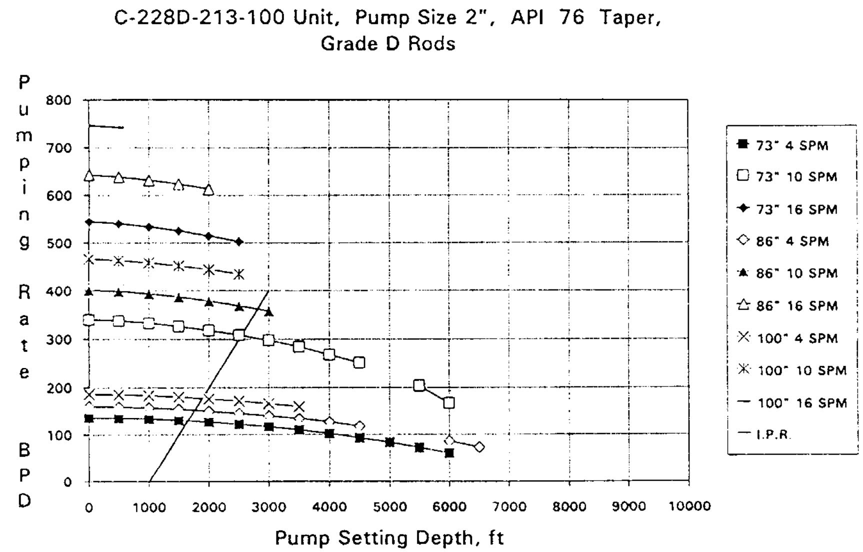

Figure 8 - System Performance Curve sheet for a C-228D-213-100 unit, 2" plunger, API 76 taper rod string, and Grade D rods