HOW TO FIND THE OPTIMUM PUMPING MODE FOR SUCKER ROD PUMPING

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ABSTRACT

The author developed a computerized technique for sucker rod system design that attains the pumping mode with the lifting efficiency being at a maximum. This optimum pumping mode gives the most economical combination of plunger size, stroke length and pumping speed. The proposed design procedure applies to conventional pumping units and assures minimum energy usage for the production of the required liquid rate to the surface.

The method presented in this paper involves designing of the rod string for each pumping mode used in the process of selecting the optimum mode. This is an important new feature, compared to previous investigations that relied on published taper lengths. The determination of pumping parameters (plunger stroke length, pumping loads, etc.) is affected by the physical characteristics of the rod string. However, string design requires the knowledge of the pumping mode: plunger size, stroke length, pumping speed. Therefore, the selection of an optimum pumping mode is an iterative process, for which a detailed solution is given in the paper.

INTRODUCTION

The aim of artificial lift design is to assure the most economical means of liquid production within the constraints imposed by the given well and reservoir. For sucker rod pumping this usually means the selection of the right size pumping unit and gear reducer, as well as the determination of the pumping mode to be used: plunger size, stroke length, and pumping speed. The size of the pumping unit and gear reducer can only be selected in the knowledge of operating conditions (loads, torques, etc.) which vary with different pumping modes. Therefore the basic task of installation design lies in the optimal determination of the pumping mode.

For surface pumps, (e.g. mud pumps) the calculation of the required plunger size, stroke length, and speed is quite straightforward. This is because pump displacement is a direct function of these variables which can be changed at will. The situation is dramatically changed in the case of sucker rod pumps, as downhole pump stroke length is far from being equal to the stroke length set at the surface. This is due to the fact that the plunger is being moved by a long elastic rod string. Pump displacement cannot be directly determined from surface parameters, and this condition is a very basic problem of a sucker rod system design.

The calculation of the liquid rate produced by a sucker rod pump relies on the accurate determination of plunger stroke length from surface data. A well-proven method for actual stroke length calculations is the procedure described in API RP 11L [1]. Generally, this calculation model gives reliable predictions as it accounts for most of the effects that have an impact on plunger movement. Therefore it is widely used to solve sucker rod pumping problems and to design installations.

This paper deals with a particularly important problem for sucker rod pumping system design: how a prescribed liquid rate can most economically be lifted from a given well. Basically, solution of this problem requires the determination of optimum values for plunger size, stroke length, and pumping speed, i.e. finding the optimum pumping mode. It is quite easy to see that a desired liquid rate can be achieved by a multitude of pumping modes. Denoting one of these as optimal is a matter of preferences, which the designer has to decide beforehand. One can say that **the optimum** pumping mode does not exist, but at the same time, there may be several optimum pumping modes, depending on actual requirements [2].

In the following, a review of the different approaches that were used to optimize pumping modes will be given. Some of them are quite simple procedures, requiring only hand calculations and the use of tables published in API documents. Others rely on sophisticated computer programs and are not readily available.

The optimization procedure described in this paper is valid for conventional pumping units and is based on RP 11L calculations, with some modifications and improvements. The goal set forth for the optimization process is to assure minimum energy usage for the production of the required liquid rate. A significant feature of the model is the designing of the rod string for each pumping mode used in the process of selecting the optimum mode. The resulting iterative calculation scheme can easily be adapted to computers, and the program developed by the author gave fair running times on personal computers.

The features and operation of the optimization method are illustrated by presenting flowcharts and an example problem.

PREVIOUS WORK

The RP 11L procedure cannot be directly applied to optimization of pumping modes, as pump displacement is a result of the calculations and not an input variable. If one starts from the desired production rate and wants to find the pumping modes which achieve that rate, a tedious trial-and-error procedure has to be followed. To ease the solution of this problem, the API published Bul. 11L3 [3], which contains several tens of thousands of precalculated pumping modes. This design book gives the pumping modes that would produce the given volumes for different liquid rates, pump setting depths, and rod taper combinations. Along with the details of the pumping mode, all the parameters that can be found with RP 11L are given. This feature allows one to select that pumping mode which is considered to be the best for producing the desired liquid rate under the conditions at hand.

The use of Bul. 11L3 tables, however, has its inherent errors, some of which are results of the limitations of the original RP 11L calculation model. These include assumptions like an anchored tubing string, pumped-off conditions, 100% volumetric efficiency, etc. Some problems arise also from the way rod string design was treated during the development of these tables. Namely, pumping modes were calculated utilizing the taper percentages given in RP 11L. But these taper lengths do not account for the effects which stroke length and pumping speed have on rod design. They only change with plunger size, as can be seen from the table of recommended taper percentages published in succeeding editions of RP 11L. Although the latest edition of RP 11L adopted a comprehensive rod design method developed by A.B. Neely [4], this situation did not change. The tables in Bul. 11L3, therefore, can contain some inherent errors and their use is limited to anchored tubing and near pumped-off conditions.

The next significant contribution to pumping mode optimization was made by M.A. Estrada [5], who used the solution of the wave equation to find the surface operational parameters of sucker rod pumping. He developed optimization tables for Mark II pumping units, and proposed the use of an Economic Index (EI) to rate the effectiveness of different pumping modes. The Economic Index includes the values of PPRL, PT, PRHP and Lifting Efficiency into a single formula, and assigns the same importance to each of these. After sorting, by ascending EI values, the pumping modes that give the desired rate, one has to select the pumping mode which is feasible under the given conditions and has the lowest possible EI value. Estrada's rating principle was later used by J.P. Byrd [6].

R.H. Gault, in one of his recent papers [7], showed the importance of proper pumping mode selection. He followed the logic of API Bul. 11L3, and used its tables. His paper proved that the selection of the right pumping mode can have a very significant effect on power usage and operating costs.

The latest contribution to the problem of pumping mode selection came from J.P. Byrd [8], who proposed a very comprehensive rating system. The Performance Effectiveness Rating System considers most of the dominant factors of sucker rod pumping, and rates pumping modes according to their Performance Effectiveness (PE) values. However, the use of his method requires preparation of optimization tables not yet available.

DESCRIPTION OF THE PROPOSED OPTIMIZATION PROCEDURE

Optimization Concept

The goal of optimization, as used in this paper, is to find that pumping mode which assures the maximum value of lifting efficiency, defined as:

$$LE = \frac{P_h}{PRHP}$$

The above requirement coincides with the case of setting the polished rod power (PRHP) to be a minimum. This is because lifting a given liquid volume from a given pump setting depth, i.e. for a given hydraulic power, lifting efficiency and PRHP are inversely proportional. The pumping mode thus determined will need the least amount of prime mover power, as the system's total energy requirement is a direct function of PRHP. Application of the proposed optimization concept, therefore, gives the most energy-efficient and thus most economical pumping mode for the production of the required liquid rate from the given pump setting depth.

The above principle was used to solve the following practical design problem: given the surface pumping unit and gear reducer, what will be the optimal pumping mode to lift the desired liquid volume. The use of a given pumping unit limits the number of possible pumping modes by imposing constraints on operational parameters like:

- maximum PPRL (limited by structural capacity),
- maximum PT (limited by torque rating),
- available polished rod stroke lengths, and
- available pumping speed range.

Selection of pumping unit and gear reducer size is also possible using the proposed technique, in which case calculations are made with no limits set to the above variables.

Improvements to RP 11L Calculations

The original RP 11L calculation method has been modified to include some features not originally available and in order to speed up calculations. These were proposed by J.D. Clegg [9], and the author [10] and include:

- the effect of wellhead pressure,
- pump volumetric efficiencies other than 100%,
- an iterative model for frequency factor calculations.

The Role of Rod String Design in the Optimization Process

In order to use the RP 11L technique for the calculation of sucker rod pumping parameters, the mechanical properties of the rod string in use have to be known. As these properties change with different taper percentages, the rod string must be designed previously. But all the proper string design procedures require plunger size, stroke length, and pumping speed as input variables. The selection of pumping modes, therefore, can only be achieved by an iterative scheme. This is not the case with Bul. 11L3 where taper percentages recommended by API were used, eliminating the need for iterations.

The optimization method proposed here accounts for the iterative nature of pumping mode selection. The rod string will be designed throughout the calculation process, thus ensuring a more exact solution of the problem. This approach reduces errors that may be present in Bul. 11L3 optimization tables under such conditions when API taper lengths (used for the development of these tables) and rod percentages actually calculated differ considerably.

Calculation Procedure

The details of the optimization method proposed in this paper will be described by presenting flowcharts of a computer program in **Figs. 1-4**. The program calculates for a given pumping unit and gear reducer all the pumping modes that would produce the required liquid volume. Basic input data are the following:

- the unit's API designation,
- available polished rod stroke length values,
- range of available pumping speeds,
- fluid properties,
- wellhead pressure,
- whether the tubing string is anchored or not,
- rod string data: API rod number,
  type of rods (coupled or continuous),
  Service Factor to be used,
- estimated pump volumetric efficiency.

After these data, the desired production data are entered:

- q_D required liquid production rate,
- L pump setting depth,
- L_{DYN} dynamic liquid level.

The calculations start with the selection of the smallest possible plunger diameter **d**, and the first polished rod stroke length **S**. (**Fig. 1**) Now only the pumping speed that would produce the desired volume has to be determined . This value is calculated in a subroutine, to be detailed later. Let's assume that this SPM (pumping speed) is already known, which means that one pumping mode has already been found. The next step is to check the pumping unit for overload conditions. In case the peak polished rod load (PPRL) is below the unit's structural capacity, and the resulting peak net torque (PT) does not exceed the rating of the gear reducer, one valid pumping mode has been found.

The above calculation scheme gives one combination of plunger size, stroke length and pumping speed that assures the production of the desired liquid rate. Further, additional operational parameters are calculated, such as polished rod horsepower (PRHP), lifting efficiency, etc. (**Fig. 2**) These parameters are then output and another pumping mode is sought. The next value of polished rod stroke length **S** is chosen, and the calculations are repeated. When all values of the pumping unit's available stroke lengths have been used, the next plunger size is selected and the whole procedure repeated.

The operation of the subroutine mentioned above is illustrated on the flowcharts in **Figs. 3-4**. These calculations find the pumping speed needed to achieve the production rate desired, for the case of given plunger size and given surface stroke length. In the first part of the procedure (**Fig. 3**), checks are made to ensure that the desired liquid rate q_D falls between the maximum and minimum pump displacements attainable with the given pumping unit. For this reason, pump displacement q_P is calculated for the lowest and highest values of available pumping speeds. If these pump displacements bracket the desired volume, an iterative calculation follows that determines the necessary pumping speed.

Fig. 4 illustrates the principle of the iteration method used. The "Regula Falsi" type of solution is applied to find the required pumping speed **N3**, starting from the given two points of the pump displacement - pumping speed function. In the knowledge of **N3**, the rod string can already be designed, as every variable that has an effect on string design is known at this point: plunger size, stroke length, pumping speed, etc. Taper lengths having been determined, the RP 11L procedure can be used to find the pump displacement q_P that corresponds to the pumping speed calculated before.

In case the pump displacement valid for pumping speed **N3** equals the desired production rate q_D, the required pumping speed, and accordingly the required pumping mode is found. Otherwise, the iteration method is repeated until the necessary pumping speed is arrived at.

At the end of the calculations described, those pumping modes will be available, which on one hand assure the pumping of the required liquid rate from the given well, and on the other, do not result in overloaded conditions using the given pumping unit and gear reducer. The program lists these pumping modes on the output, from which the optimal one with the highest value of the lifting efficiency can be determined. This optimal pumping mode will result in the least amount of electric power usage and power costs as well. In case this pumping mode is not feasible for some reason (e.g. restriction on tubing size) another one is selected which has the next highest lifting efficiency value.

EXAMPLE PROBLEM

To illustrate the optimization procedure and the developed computer program, an example problem will be shown. In this example the same input data are used as those given by R.H. Gault [7]. These data involved a desired liquid production of 500 bpd from 6000 ft pump setting depth with an anchored tubing string and pumped-off conditions. Pumping this amount of liquid requires a hydraulic horsepower of 22.1 HP.

To facilitate the selection of pumping unit and gear reducer sizes for the job, the program was run with no limits set on torque rating and structural capacity values. The pumping modes with the best and worst lifting efficiency, selected from the calculated ones are the following:

	Best Mode	Worst Mode
API Rod No.	76	85
Pump Size	2 3/4"	1 1/4"
Stroke Length	144 in	144 in
Pumping Speed	6.8 SPM	19.9 SPM
PRHP	23.0 HP	65.8 HP
Lifting Efficiency	96.1%	33.6%
Required Unit Size	C 912D-305-168	

Using the best pumping mode, the energy input at the polished rod is only slightly greater than the hydraulic power (22.1 HP), showing a very efficient operation. On the other hand, the worst mode uses almost three times as much energy as the best one. It is also interesting to see, that these two extreme pumping modes both require the same size of pumping unit. As total energy costs are directly related to polished rod horsepower, big savings can be realized by choosing the right pumping mode.

Fig. 5 shows the maximum values of lifting efficiencies obtained for different rod combinations vs. pump size. It is clearly seen that increasing the plunger size increases maximum lifting efficiency for all API rod numbers. Therefore, use of bigger plunger diameters with correspondingly slower pumping speeds is always advantageous because these result in lower energy requirements.

Another observation, in line with practical experience, is that use of heavier rod strings (85 or 86 instead of 75 or 76) can greatly increase the power requirements for smaller pumps. The difference is not so pronounced for bigger pumps, as in those cases rod weight becomes a smaller fraction of the total load.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Significant operating cost savings can be realized by using the optimum pumping mode that assures maximum lifting efficiency.

2. The calculation procedure and the computer program developed in this paper provide a viable alternative over using API Bul. 11L with additional features that can improve the accuracy of pumping system design, such as:

- the rod string is designed during optimization,
- the case of unanchored tubing is also solved,
- handles dynamic liquid levels above pump setting depth, and
- handles pump volumetric efficiencies less than 100%.

The limitations of the developed optimization method are basically those of the RP 11L procedure.

NOMENCLATURE

d	Plunger Diameter, in
L	Pump Setting Depth, ft
L_{DYN}	Dynamic Liquid Level, ft
LE	Lifting Efficiency, %
N	Pumping Speed, SPM
P_h	Hydraulic Power, HP
PPRL	Peak Polished Rod Load, lbs
PRHP	Polished Rod Horsepower, HP
PT	Peak Net Torque, in-lbs
q_D	Desired Liquid Production Rate, bpd
q_P	Pump Displacement, bpd
S	Polished Rod Stroke Length, in

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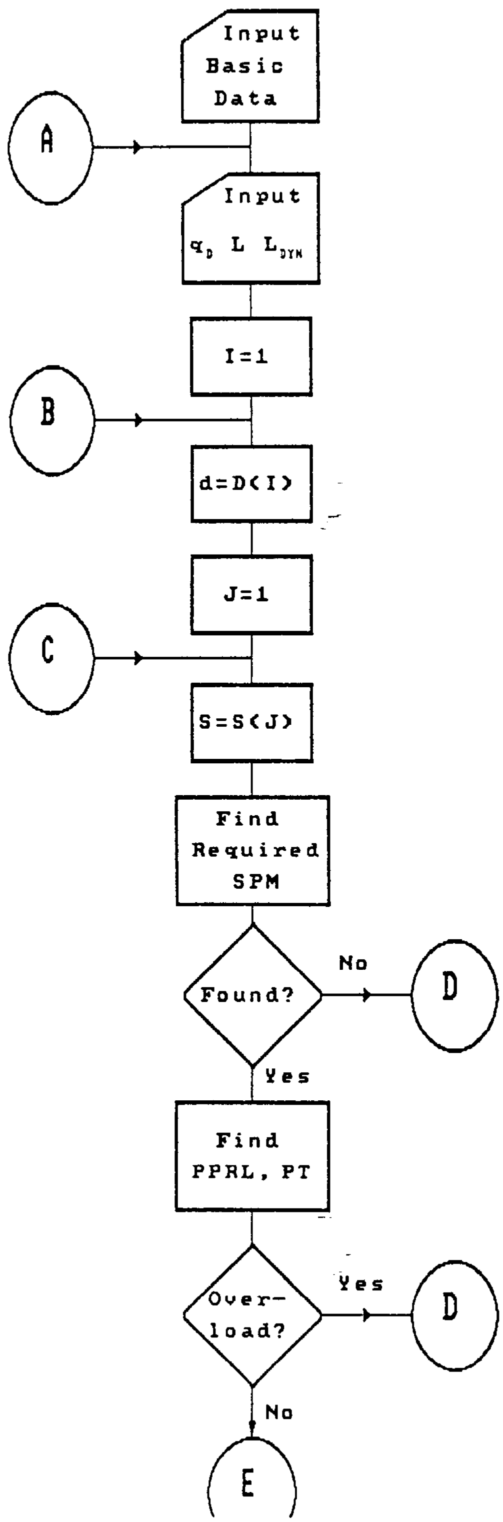

Figure 1 - Flow chart of the optimization program

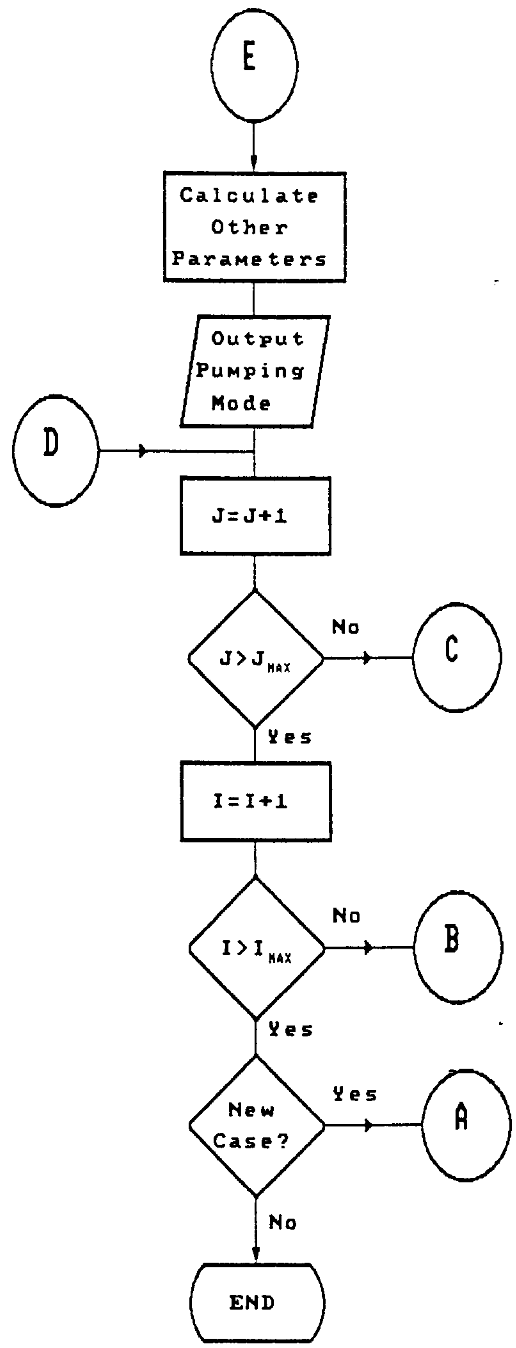

Figure 2 - Flow chart of the optimization program (continued)

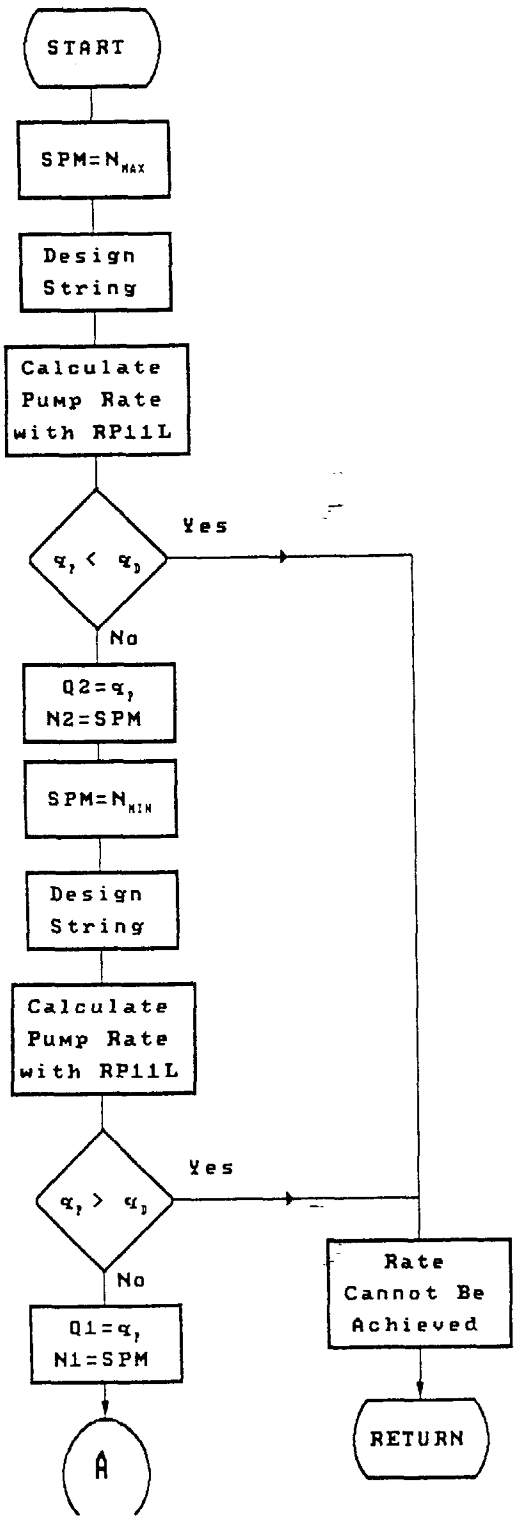

Figure 3 - Flow chart of the subroutine that calculates the required pumping speed for given plunger size and stroke length

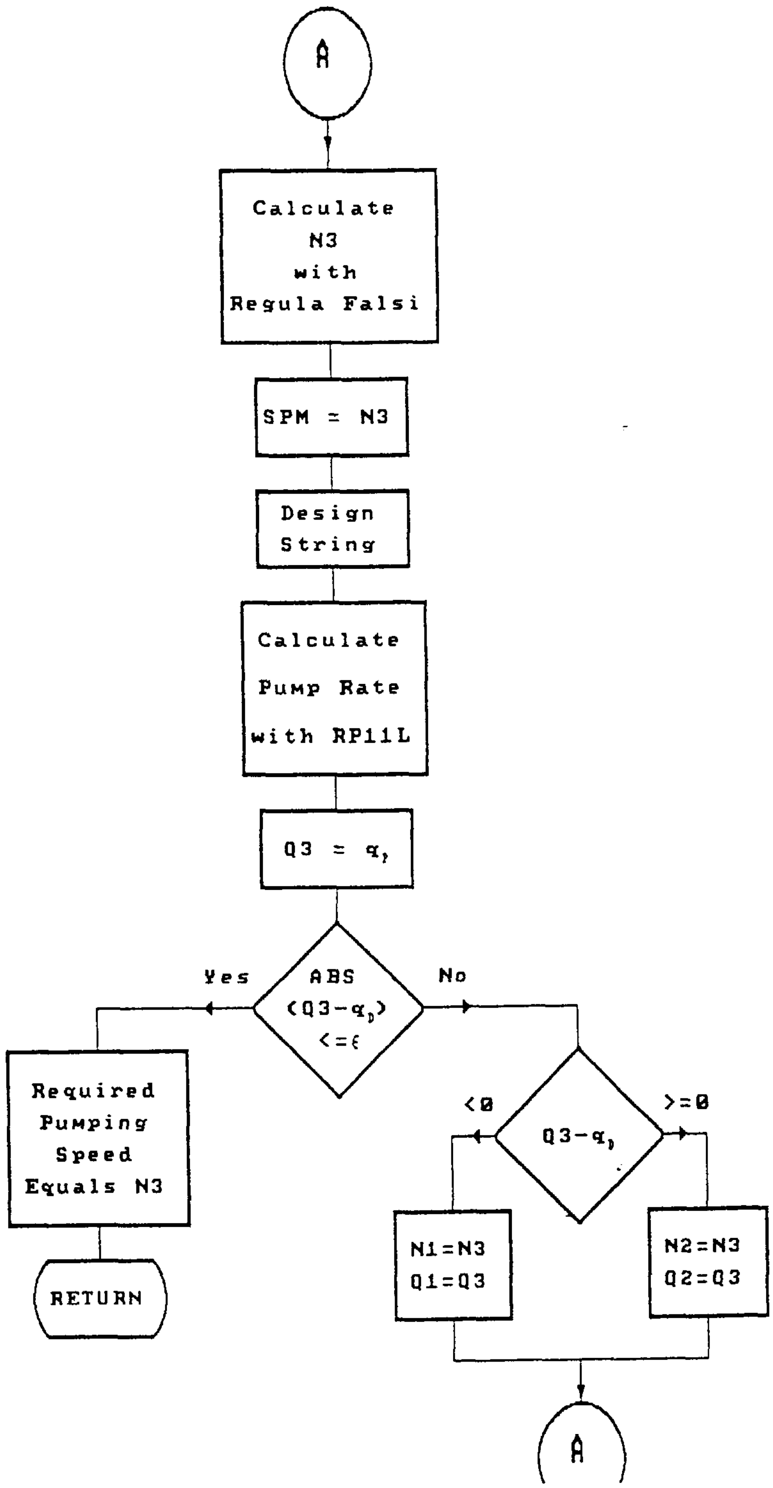

Figure 4 - Flow chart of the subroutine that calculates the required pumping speed for given plunger size and stroke length (continued)

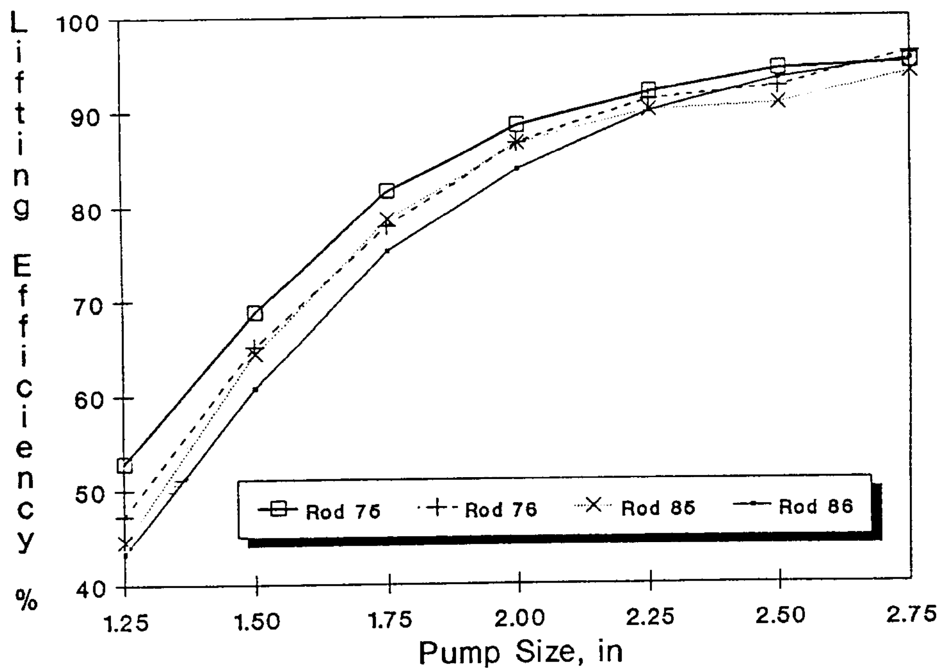

Figure 5 - Maximum lifting efficiency values for different rod combinations vs. pump size for the example problem