SUBSURFACE HYDRAULIC PUMPING DIAGNOSTIC TECHNIQUE*

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INTRODUCTION

Hydraulic pumping made its appearance as a method of oilwell artificial lift in the early 1930's. Since that time this method has found wide acceptance, especially in deep, high volume pumping. Because the unit is located near the bottom of the well, understanding the operation and condition of the downhole unit can often be a problem for the producer. This paper presents a well-site analytical method using pressure and production data to determine useful information about the overall condition of the hydraulic pumping system along with the well's potential. Thus, by thoroughly understanding equipment and well conditions, the producer is in a better position to reach his goal of maximizing profit.

The hydraulic pumping system analyzed in this paper consists of a downhole hydraulic reciprocating engine directly connected to a reciprocating pump which functions as a unit. There are many configurations of downhole units available such as tandem engines with single pumps, tandem pumps with single engines, tandem pumps with tandem engines, and a large selection of power ratios. Also, downhole tubular arrangements vary depending on application such as casing free, fixed casing, parallel and fixed insert. Since the operation is basically the same, the method discussed in this paper applies generally to all. Also of importance are the two types of power fluid arrangements, i.e. open and closed systems. The closed system keeps the power fluid separate from produced fluids as compared to the open system which mixes produced fluid and power fluid as they are discharged from the unit. Most systems are of the open type because of simplicity of design and reduced equipment costs. This paper discusses the open type only; but with minor modifications, the closed power fluid arrangement can be analyzed as well.

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DESCRIPTION OF EQUIPMENT AND IMPLEMENTATION OF TECHNIQUE

Figure 1 is a schematic drawing of portable analytical equipment. The functions of the major components are described as follows:

1. Strain gauge type pressure transducers are temporarily installed at the wellhead to accurately measure changes in power fluid and flowline pressures versus time.
2. A two-channel strip chart recorder is used to excite the transducers, amplify the return signal and permanently record pressure data.
3. A digital computer is programmed with a mathematical model which uses pressure data and other information supplied by the producer such as well test, fluid properties and downhole equipment arrangement.
4. A teleprinter is used to input data into the computer and to output results.

Other components include a punched tape photoreader for loading programs quickly, vehicle, electric power plant, air conditioning unit and miscellaneous tools.

Since all equipment is portable, the complete analysis can be performed on the well site. An on-site analysis has two paramount advantages. First, analytical results are available immediately. Second, oil company personnel such as engineers, foremen and lease operators can participate in the analysis by contributing their knowledge of well history, prior downtime and other mechanical and reservoir characteristics.

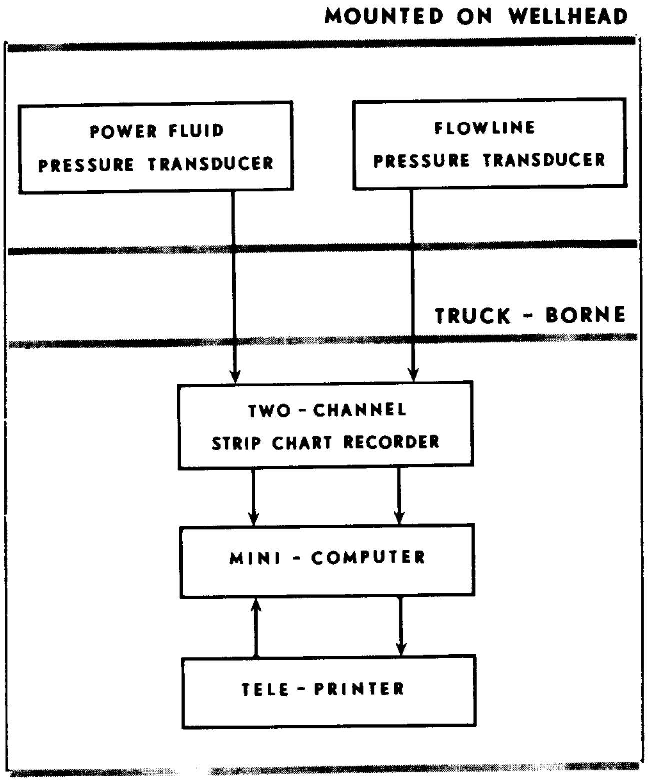

FIG. 1—SCHEMATIC OF PORTABLE ANALYTICAL EQUIPMENT

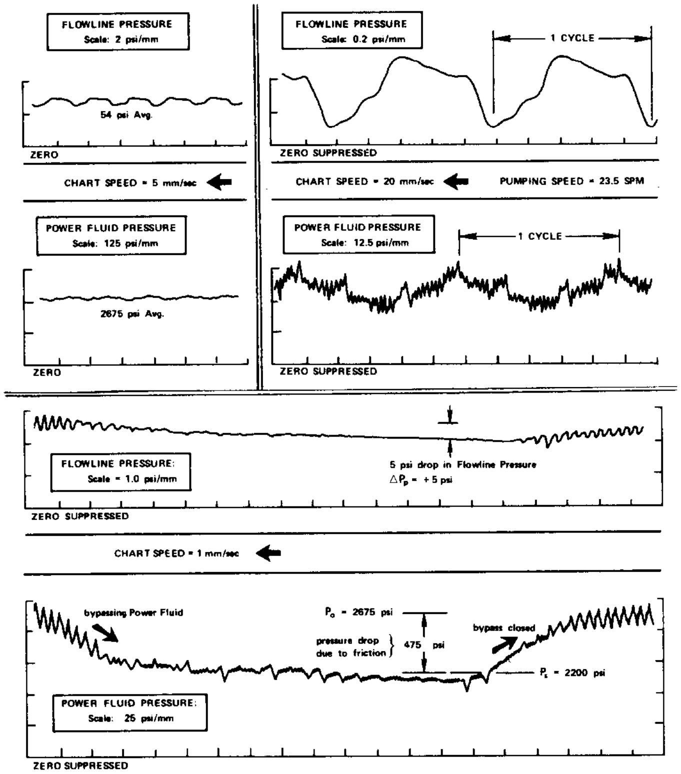

FIG. 2—PRESSURE MEASUREMENTS ON TYPICAL WELL

INTERPRETATION OF SURFACE PRESSURE DATA

Wellhead power fluid and flowline pressures are recorded simultaneously. Initially, absolute pressure measurements are made to determine operating pressures. Next, the pressure scale factors are reduced to amplify the pressure fluctuations from the downhole pump and engine. In order to expand the pressure scale, zero must be suppressed. The last pressure measurements taken are for determining the total friction in the system. These pressures are commonly referred to as the "last stroke" or "stall" pressures. Figure 2 is an example of pressure measurements taken on a typical well.

An accurate pumping speed of 25.5 SPM can be easily measured in Fig. 2 even with the standard bourdon-type pressure gauge. However, in certain installations the bourdon-type gauge may be misleading in determining pumping speed. Figure 3 is an example where the actual pumping speed of 30.8 SPM was half the reported pumping speed of 62 SPM. In this case each pressure pulse (shifting valve pressure reflection) was interpreted as a complete cycle. However, by studying the pressure recordings from the strain gauge transducers, the true cycle was determined accurately. Figure 4 shows a case where the ordinary pressure gauge was inadequate for measuring pumping speed. A relatively small downhole unit was set below 10,000 feet. Thus, the pressure responses from the pump were partially damped out. In addition, pumping speed measurements were further complicated by surface plunger pump pulses masking or obscuring the already faint subsurface signals. In these cases the time based recordings of pressure obtained from strain gauge transducers have proven more reliable than bourdon gauges in determining accurate pumping speeds.

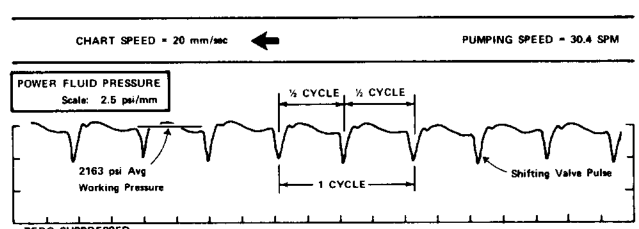

FIG. 3—MEASURING PUMPING SPEED

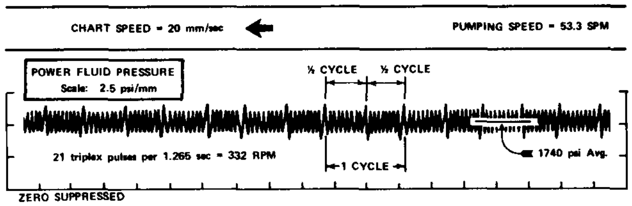

FIG. 4—MEASURING PUMPING SPEED WITH BACKGROUND NOISE

Abnormal downhole unit operation can sometimes be indicated by visual interpretation of pressure recordings. For example, Fig. 5 shows an erratic pumping condition wherein pump cycles are not repetitive. This can indicate a malfunctioning reversing valve or sometimes a pumped-off or overdisplaced condition. Figure 6 reflects a severely worn pump valve because one stroke (half cycle) takes much less time than the other stroke (half cycle). This particular unit is of the balanced double-acting type where the upstroke and downstroke should take about the same amount of time. A hard fluid pound occurring with a balanced double-acting unit (incomplete pump fillage and low pump intake pressure) is shown in Fig. 7. A pressure reflection of the fluid pound occurs between shifting valve pulses.

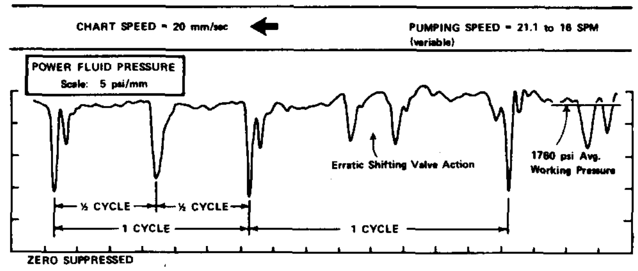

FIG. 5—ERRATIC PUMPING CONDITION

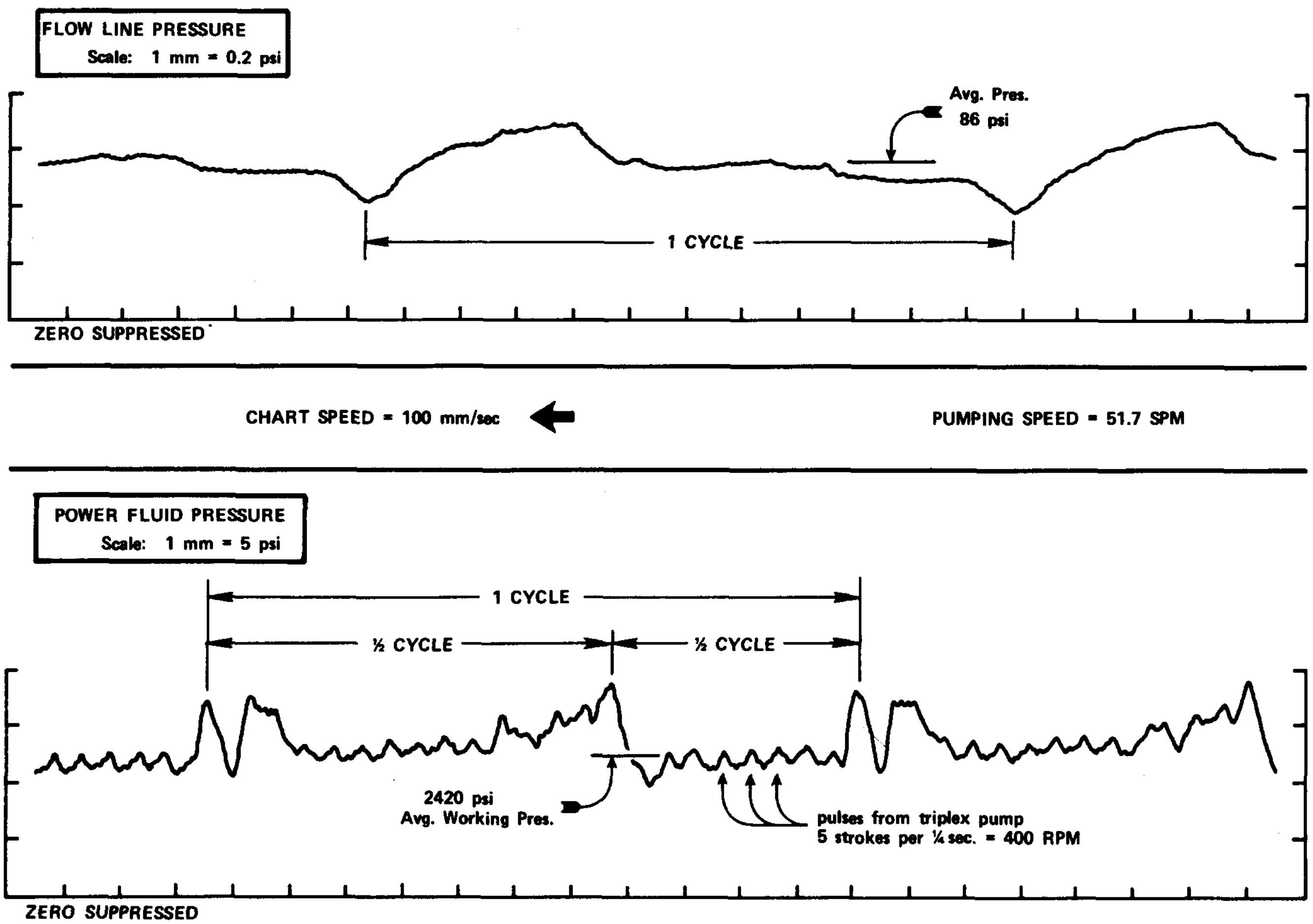

FIG. 6—SEVERELY WORN PUMP

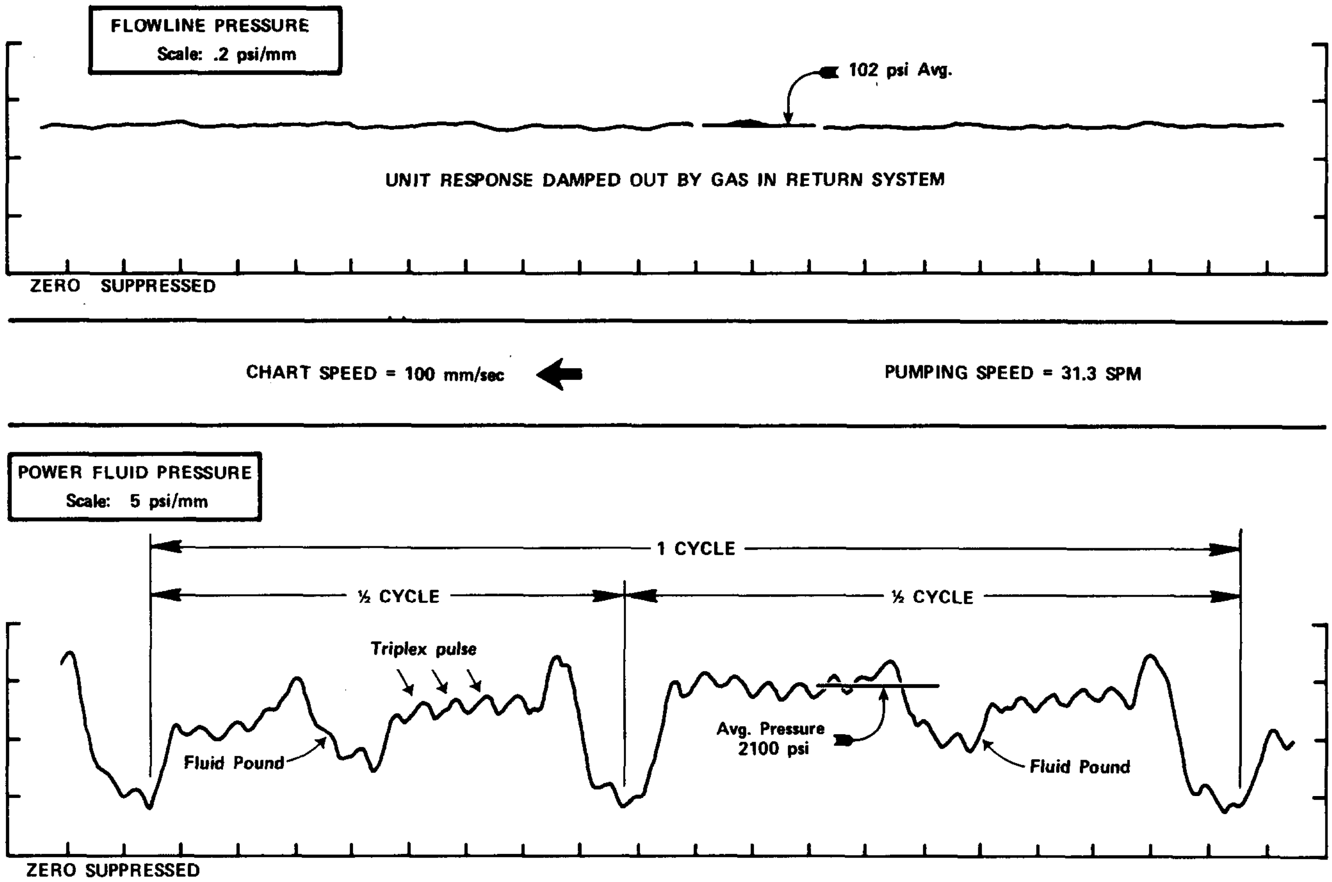

FIG. 7—FLUID POUND

Friction loss across the downhole unit can be calculated from the "stall" or "last stroke" pressure and computed tubular friction losses. Referring again to Fig. 2, the "stall" pressure can normally be determined by gradually reducing the power fluid flow rate to the downhole engine until the unit ceases to stroke. The measurement should be performed quickly to avoid an appreciable change in the pump intake pressure. The difference between the normal operating pressure and the "stall" pressure is a measure of the total frictional effects in the system along with any changes in the flowline pressure. Thus, by using the following equation* the friction loss across the downhole unit can be calculated.

$$F_u = P_o - P_s - F_P - (1 + A_p/A_e)(F_r + \Delta P_f) \qquad (1)$$

ΔP_f is negative if P_f increases and positive if P_f decreases while measuring "stall" pressure. A unit may not "stall" if the pump is abnormally worn (excessive fluid slippage past plunger and valves).

*Symbols are defined in Nomenclature section.

This, too, is a useful diagnostic clue. If excessive pump wear has occurred, the friction loss across the downhole unit can be estimated from the manufacturer's friction loss curves. These curves should be used with caution because well conditions sometimes differ from the conditions under which the friction losses are measured in the laboratory. These differences include viscosity, pump efficiency (friction losses decrease as pump efficiency is reduced) and the degree of engine and pump wear.

In installations powered by a single power fluid plunger pump other useful information can be obtained such as pump RPM, operating pressure (if near well location) and condition of the valves. Figure 8 shows a triplex pumping speed of 424 RPM and a leaky valve. The leaky or worn valve is indicated by a weak discharge pressure pulse when compared to the pressure pulses from the other two plungers. If more than one plunger pump is discharging into a common system, the pressure pulses in the system mingle and therefore cannot be easily interpreted.

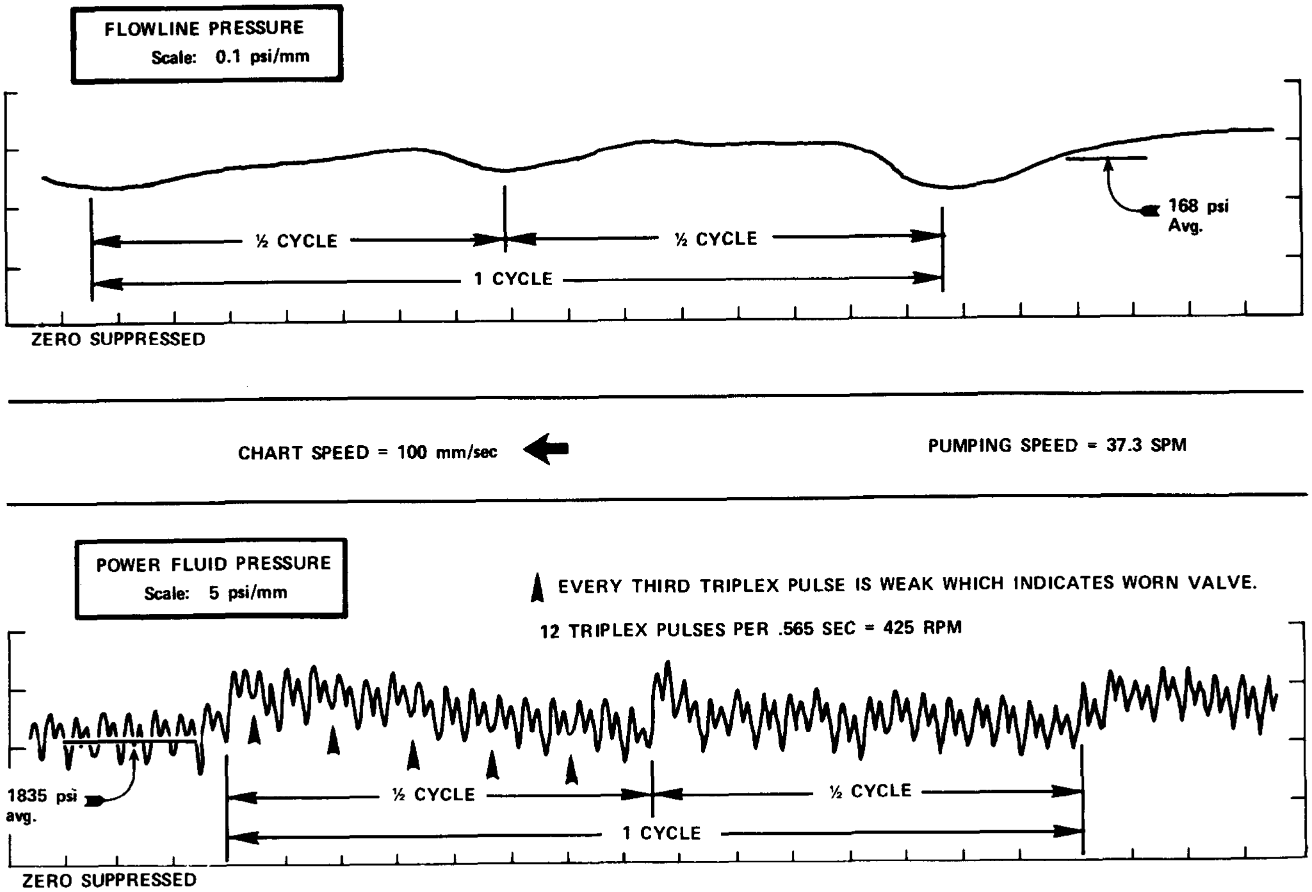

FIG. 8—INTERPRETATION OF PRESSURE RESPONSES FROM TRIPLEX PLUNGER PUMP

Alternate equipment for measuring surface power fluid changes for visual interpretation, involving an acoustical well sounder, is described by Chastain[1].

THE ANALYTICAL METHODS

To complement the information that is obtained by visual interpretation of surface pressures, analytical methods involving mathematical models of the pumping system are employed. The analytical phase is usually accomplished in two steps. The first step is one of diagnosis, i.e. of determining the operating status of the installation as it currently exists. The second stage is one of prediction and optimization based on what has been learned in the diagnostic phase.

A principal diagnostic indicator is pump intake pressure which is determined from pressure balance considerations as expounded by Coberly.[2] This pressure is given by the following equation:

$$P_p = (1 + A_e/A_p)(HG_r + F_r + P_f) - (A_e/A_p)(P_o - HG_p - F_p - F_u) \quad (2)$$

Figure 9 is a logic diagram for the pump intake pressure calculation procedure. In obtaining a solution to Eq. (2), the pump is used as a meter. At a given pump intake pressure the amount of free and solution gas passing through the pump is determined from pump displacement, produced volumes corrected to downhole conditions and natural gas laws. This establishes the return line gas liquid ratio from which an average return line gradient, G_r, can be established using modified flowing gradient curves. The various computed quantities are then substituted into Eq. (2) in an iterative process until the equation is satisfied.

The remaining diagnostic clues pertain to friction losses and efficiencies in the downhole tubulars and equipment. These are by-products of the calculation for pump intake pressure.

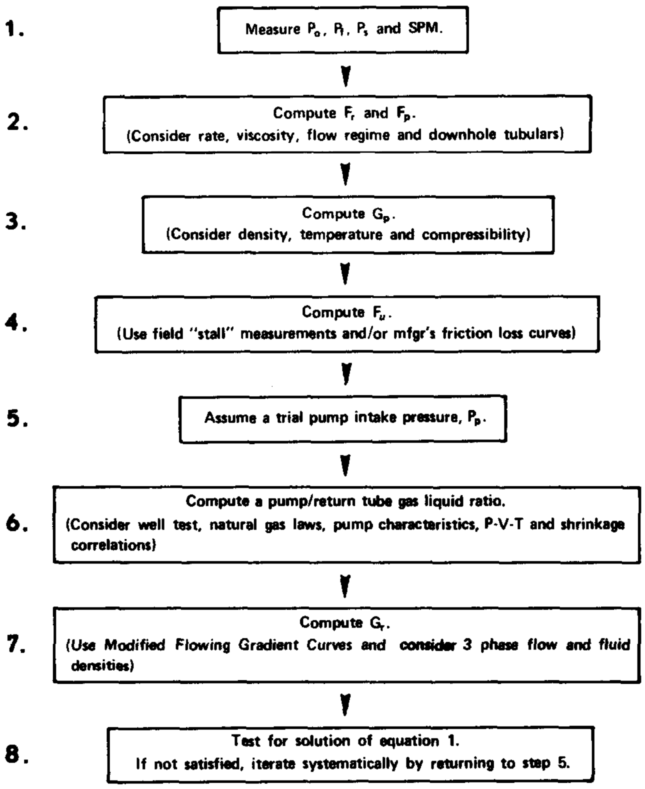

FIG. 9—COMPUTATION PROCEDURE FOR DIAGNOSTIC METHOD

The predictive/optimization model is slightly more detailed than the diagnostic model just described. This is because the well's behavoir, i.e. producing performance versus producing pressure, is also simulated.

Figure 10 is a logic diagram of the predictive/optimization procedure. The main requirement is to establish a producing pressure wherein the volume of produced fluids (oil, water and gas at ambient pump intake pressure) equals the desired pump displacement rate (BPD). Important items at this stage are anticipated downhole pump mechanical and free gas separation efficiencies. Equation (3) is then solved to establish wellhead operating pressures, power oil rates and other items of predictive and optimization interest.

$$P_o = (1 + A_p/A_e)(HG_r + P_f + F_r) - HG_p + F_p + F_u - (A_p/A_e) P_p \qquad (3)$$

In the methods described above, PVT and shrinkage correlations are stored in the computer in a compact nondimensional form similar to those presented by Cronquist.[3] Well performance models used can either be based on a constant productivity index (PI) or Vogel's method.[4] The latter considers the important effect of declining PI with pressure drawdown below the bubble point.

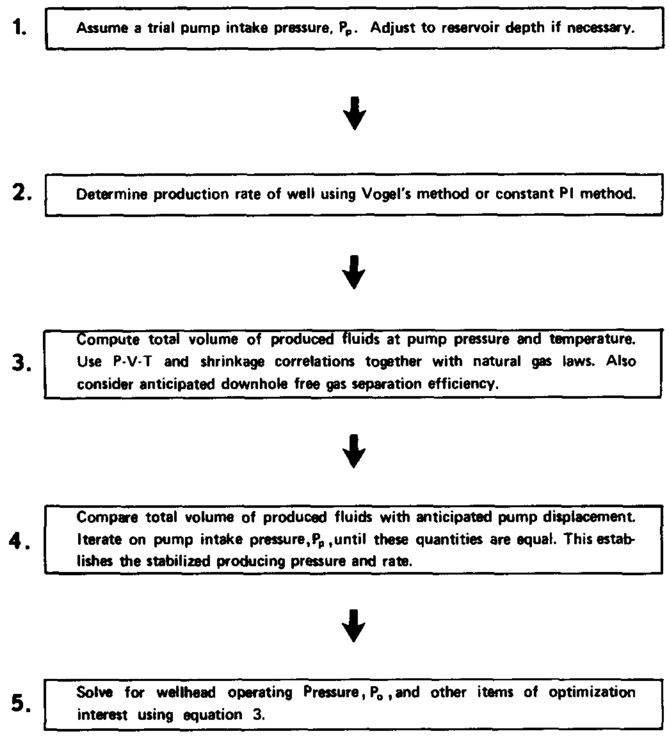

FIG. 10—COMPUTATION PROCEDURE FOR PREDICTIVE/OPTIMIZATION METHOD

Another diagnostic method is described by Gibbs.[5] This method employs a wave equation solution using Fourier analysis to quantitatively interpret pressure and flow rate fluctuations in the power oil system.

EXAMPLE ANALYSIS

By way of example, an actual analysis is shown in Tables 1 and 2 and Fig. 11.

Table 1 consists primarily of computer output in the diagnostic phase. Computed data include pump intake pressure, pump and engine efficiencies (with and without crude shrinkage considered) and friction losses in various parts of the system. The pump intake pressure is an important indicator of the well's potential for a production increase. Pump and engine efficiencies along with interpretations of pressure recordings

TABLE 1—COMPUTER OUTPUT - DIAGNOSTIC PHASE

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SUBSURFACE OPERATING CONDITIONS *******

 PUMP PERFORMANCE -

  PUMP INTAKE PRESSURE(PSI):  1306      PUMPING SPEED(SPM):  29.6
  GAS INTERFERENCE:   NONE              FLUID POUND:  NONE
  GROSS PUMP DISPLACEMENT(BPD):   426
  PUMP EFFICIENCY BASED ON TEST PRODUCTION(%):  78.3
  PUMP EFFICIENCY WITH OIL SHRINKAGE CONSIDERED(%):  98.0

 ENGINE PERFORMANCE -

  GROSS ENGINE DISPLACEMENT(BPD):  634
  ENGINE EFFICIENCY(%):  88.2

 DOWNHOLE FRICTION LOSSES -

  PRESSURE LOSS IN RETURN SYSTEM(PSI):  1
  PRESSURE LOSS IN POWER OIL TUBING(PSI):  34
  PRESSURE LOSS ACROSS BOTTOMHOLE UNIT(PSI):  233

 FLUID PROPERTIES -

  OIL SHRINKAGE FACTOR AT PUMP INTAKE PRESSURE:  1.251
  AVERAGE GRADIENT OF RETURN FLUIDS(PSI/FT):  .307

SURFACE OPERATING CONDITIONS **********

 WELLHEAD PRESSURE(PSI):   1200
 FLOWLINE PRESSURE(PSI):   128

SUBSURFACE EQUIPMENT ******************

 PUMP DESCRIPTION:       FIXED CASING, 4 X 2 X 1-3/4
 PUMP SETTING DEPTH(FT):  9340    PACKER DEPTH(FT):  10818
 CASING DIAMETER(IN):  7          PBTD(FT):  12358
 TUBING DIAMETER OR DIAMETERS(IN): 2-3/8
 COMPLETION TYPE:    PERFORATIONS FROM 12346 FT  TO  12352 FT
 DOWNHOLE GAS SEPARATOR DESCRIPTION: NONE, NOT VENTED

PRODUCTION DATA ***********************

 TEST DATE: 3/14/73
 BOPD:   334      BWPD:  0        BPOPD:    719       SPM: 30
 GOR:   500       OIL GRAVITY(API):  45.5    WATER GRAVITY(SG): 1.043
 BUBBLE POINT(PSI): 1300          SOLUTION GOR AT BUBBLE POINT:  500
 FORMATION VOLUME FACTOR AT BUBBLE POINT:  1.30
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TABLE 2—COMPUTER OUTPUT - PREDICTIVE PHASE

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                    <<< CURRENT CONDITIONS >>>

PUMP INTAKE PRES(PSI):   1306      AVG RESERVOIR PRES(PSI): 2500
BOPD:   334          BWPD:  0                BFPD:  334

                    <<< DESIGN ASSUMPTIONS >>>

PUMP TYPE:  FIXED CASING, 4 X 2-3/8 X 2-3/8
SETTING DEPTH(FT):  9340           GRAD BELOW PUMP(PSI/FT):  .346
PUMP MECH EFF(%):  95              ENGINE MECH EFF(%):   90
TEMPERATURE AT PUMP(DEG F):   150  POWER OIL GRAV(DEG API):  45.5

WELL INFLOW MODEL USED:   VOGEL'S METHOD

GOR:    500                        OIL CUT(%):   100
DOWNHOLE FREE GAS SEPARATION FACTOR(VOL PUMPED/TOTAL VOL):  1
OIL GRAVITY(DEG API):  45.5        WATER GRAVITY(SG):   N/A
BUBBLE POINT(PSI):   1300          SOLUTION GOR:  500
FORMATION VOLUME FACTOR(BBL/BBL):  1.3

                  <<< PERFORMANCE PREDICTIONS >>>

MAX POTENTIAL AT ZERO RESERVOIR PRESSURE(BPD):   3689

PUMP INTAKE PRES(PSI):   1148      PROD RESERVOIR PRES(PSI):  2189
BOPD:    675         BWPD:    0              BFPD:  675

WELLHEAD PRESSURE(PSI):  2118      FLOWLINE PRESSURE(PSI):  250
SPM:   35                          BPOPD:     1281

GROSS PUMP DISPL(BPD):   1138      GROSS ENGINE DISPL(BPD):  1153
NET LIQUID DISPL(BPD):    834      FREE GAS PUMPED(BPD):   259
PUMP EFFICIENCY W/O CONSIDERING SHRINKAGE(%):   59.3
PUMP EFFICIENCY CONSIDERING SHRINKAGE(%):   73.3
OIL SHRINKAGE FACTOR-PUMP TO TANK(BBL/BBL):   1.2358

PRESSURE LOSS IN RETURN SYSTEM(PSI):   3
PRESSURE LOSS IN POWER OIL SYSTEM(PSI): 99
PRESSURE LOSS ACROSS BOTTOMHOLE UNIT(PSI): 270
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are used to evaluate the conditions of the downhole unit. Friction losses are calculated in the power fluid tubing, in the return system and across the downhole unit. Other information presented includes accurate measurements of unit pumping speed, working power fluid pressure and flowline pressure. Documentary data are also included which consist of subsurface equipment description, production test and produced fluid properties.

Figure 11 is an annotated pressure versus time recording of a representative pump cycle.

Once current operating conditions are evaluated as described above, the predictive computer program is used to suggest strategies for optimizing well and equipment performance. For the example well a calculated pump intake pressure of 1306 psi and complete pump fillage (no gas interference) indicate that more production is available by increasing pump displacement. Table 2 is a computer prediction of expected results if displacement is increased from 426 to 1138 BPD with a unit having a A_e/A_p ratio of 1. Since a static reservoir pressure of 2500 psi is known, an IPR can be determined for the well. Vogel's method is selected to predict additional potential with increased pressure drawdown. This method is normally used to potential wells producing mostly oil; however, in high water-cut wells (water-cut exceeding 70%) a constant PI is normally preferred. The PVT properties of the crude and the amount of free gas vented are also considered. In the example well no free gas is vented. Therefore, as the well is drawn down below the bubble point with added displacement, the adverse effects of free gas interference and of crude shrinkage on pump efficiency are considered.

Larger equipment was installed in this well which increased pump displacement from 426 BPD to 1001 BPD. Production increased from 334 BOPD to 650 BOPD. The pump intake pressure was lowered from 1306 psi to 1148 psi with a corresponding increase in wellhead operating pressure from 1200 psi to 2180 psi. As shown in Table 2, predicted results compare closely with the above measured results.

Other applications of these methods are described by Gill.[6]

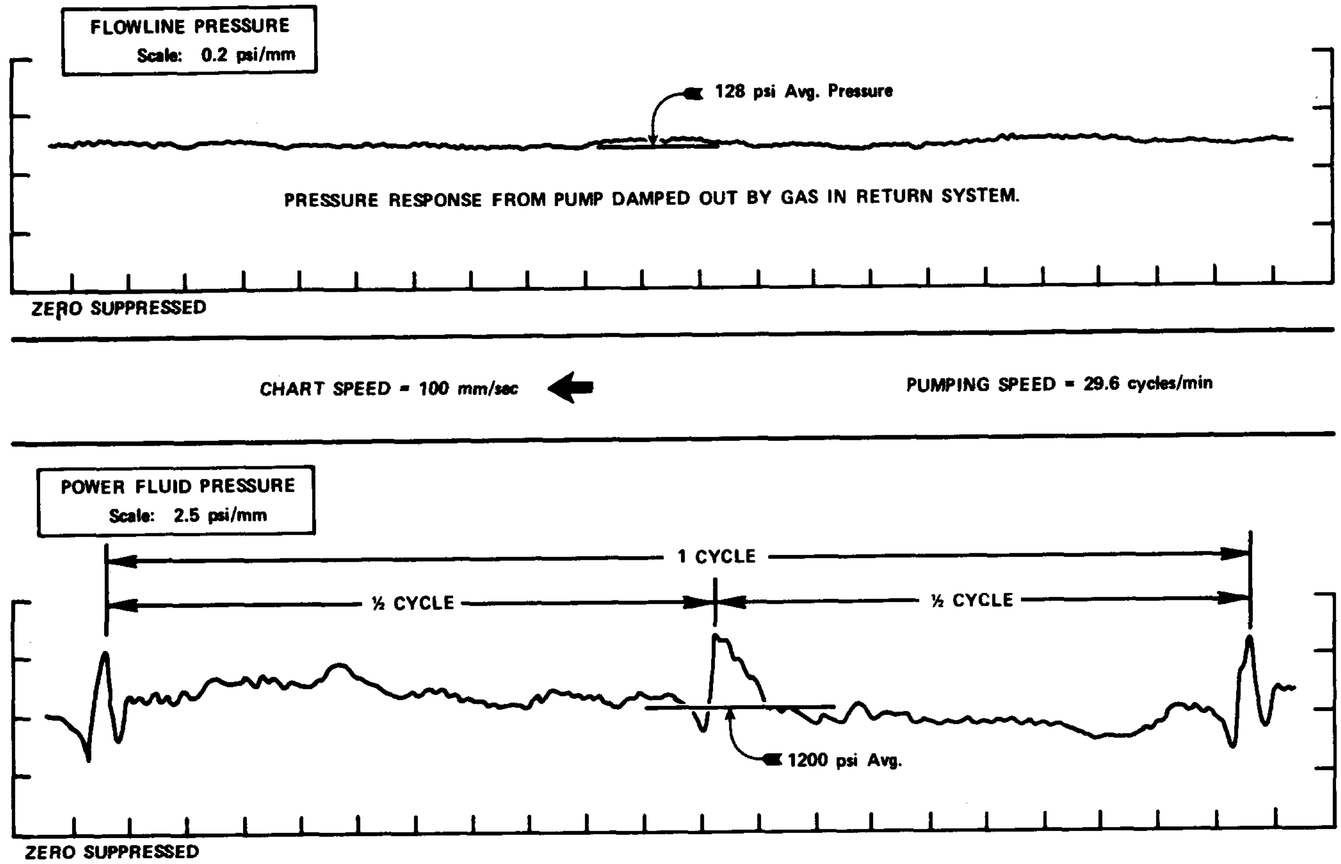

FIG. 11—ANNOTATED PRESSURE RECORDING OF REPRESENTATIVE PUMP CYCLE

CONCLUSIONS

The on-site hydraulic diagnostic technique is a unified analysis of mechanical equipment and well performance and capability. Thus, by the use of this method it is easier for the oil producer to approach the goal of maximizing profit from hydraulic pumping wells.

NOMENCLATURE

- A_e - Area of engine plunger, in.^{2}
- A_p - Area of pump plunger, in.^{2}
- G_p - Average gradient of power fluid column, psi/ft
- G_r - Average gradient of return fluid column, psi/ft
- F_p - Friction loss in power fluid tube, psi
- F_r - Friction loss in return fluid tube, psi
- F_u - Friction loss across bottomhole unit, psi
- H - Unit setting depth, ft
- P_o - Operating pressure at wellhead, psi
- P_f - Flowline back pressure at wellhead, psi
- P_p - Pump intake pressure, psi
- P_s - "Stall" or "last stroke" pressure at wellhead, psi
- ΔP_f - Change in flowline back pressure while measuring "stall" pressure, psi

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