THE THEORY, HARDWARE, AND APPLICATION OF THE CURRENT GENERATION OF OIL WELL JET PUMPS

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ABSTRACT

This paper will present a summary of jet pump theory and performance, and an algorithm for applying jet pumps to the wide range of conditions encountered in oil wells. Nozzle and throat sizes available from National Production Systems, Kobe, Inc., and Guiberson Hydraulic Pumping Systems, the three major suppliers of oilfield jet pumps, will be presented. Appendices will include hand-held calculator application programs for a TI-59 and an HP-41C.

Comparisons between the predictions from the calculator programs and the sophisticated programs used by the pump manufacturers as well as actual well data, will demonstrate the applicability and limitations of the techniques presented in this paper. The discussion will include potential sources of error and the sensitivity of the calculations to uncertainties in the well data.

INTRODUCTION

Hydraulic pumping systems for artificial lift consist of a fluid reservoir on the surface, a high pressure surface pump that transmits the fluid downhole, and a downhole pump driven by the high pressure fluid. The power fluid and the produced fluid both flow to the surface after passing through the downhole unit . Conventional downhole pumps have been of the positive displacement type, employing reciprocating pistons. In the last 10 years, however, hydraulic pumping systems using downhole jet pumps have been widely employed.

A typical downhole jet pump is shown in Fig. 1. Having no moving parts, jet pumps are rugged and tolerant of corrosive and abrasive well fluids. They are compact and adaptable to all existing hydraulic pump bottom hole assemblies. Jet pumps have high volume capabilities and handle free gas well, but they typically require higher pump intake pressures than conventional pumps to avoid cavitation. Also, their efficiency is lower than that of positive displacement equipment, leading to higher surface horsepower requirements. It has been observed, however, that in some wells with substantial gas production, they may actually require less power.

APPLICATION CONSIDERATIONS

As a type of dynamic pump, jet pumps have characteristic performance curves similar to electric submersible pumps. An example is shown in Fig. 2. Note that an infinite family of curves is possible, depending on the nozzle pressure. Different sizes of throats used in conjunction with a given nozzle give different performance curves. The curves are generally fairly flat, especially with the larger throats, making the jet pump sensitive to changes in intake or discharge pressure. Since fluid densities, gas, and viscosities affect the pressures the pump sees, the calculations to simulate performance are complex and iterative in nature, lending themselves to a computer solution.

Since the actual sizes of components and the associated performance curves have historically been proprietary with the pump manufacturers, it has been difficult for the production engineer to evaluate jet pumping systems in designing artificial lift systems for his wells. However, reasonable accuracy in application calculations can be obtained on hand held calculators if the commercially available sizes and their performance characteristics are available. This paper addresses that need.

THEORY OF JET PUMPS

In the following discussion, reference to Fig. 4 will be helpful. The jet pump is a hydrodynamic rather than hydrostatic type of pump and operates principally through momentum transfer between two adjacent fluid streams. High pressure power fluid passing through the nozzle has its potential energy (pressure energy) converted to kinetic energy in a jet of fluid at high velocity. Well fluid mixes with the power fluid in a constant area throat or mixing tube and momentum is transferred to the well fluid, causing an energy rise in it. As the mixed fluids exit the throat, they are still at a high velocity and thus contain substantial kinetic energy. The fluids are slowed in an expanding area diffuser which converts the remaining kinetic energy to static pressure sufficient to lift fluids to the surface. Design variables include the sizes of the nozzle and throat and the ratio of their flow areas as well as component shapes, angles, lengths, spacing, finishes, and materials. Assuming that the components have been optimized through testing, then the flow areas and their ratios are of interest for application purposes. Through selection of appropriate flow areas and ratios, the configuration of the pump can be optimized to match the well conditions.

The physical sizes of the nozzles and throats determine the flow rates while the ratio of their flow areas determines the trade off between produced head and flow rate. If, for example, a throat is selected such that the area of the nozzle is 60% of the throat area, a relatively high head, low flow pump will result. There is a comparatively small area around the jet for well fluids to enter, leading to low production rates, and with the energy of the nozzle being transferred to a small amount of production, high heads will be developed. Such a pump is suited to deep wells with high lifts.

If, on the other hand, a throat is selected such that the area of the nozzle is only 20% of the throat area, more production flow is possible, but, since the nozzle energy is being transferred to a large amount of production, lower heads will be developed. Shallow wells with low lifts are candidates for such a pump.

Any number of such area combinations are possible to match different flow and lift combinations. Attempting to produce small amounts of production with a nozzle-throat ratio of 20% will be inefficient due to high turbulent mixing losses between the high velocity jet and the slow moving production. Conversely, attempting to produce high production rates with a nozzle-throat ratio of 60% will be inefficient due to high friction losses as the produced fluid moves rapidly through the relatively small throat. Optimal ratio selection involves a tradeoff between these mixing and friction losses.

The cavitation characteristics of the pumps must also be considered. Cavitation will occur when the velocity of the produced fluid entering the throat around the power fluid jet is high enough that the static pressure in the fluid falls to its vapor pressure. This is a choked flow condition and cavitation damage to the throat is likely.

MATHEMATICAL REPRESENTATION

Since each manufacturer of jet pumps offers a large number of nozzle sizes and five or more throats for each nozzle, and because there is no standardization of these sizes between suppliers, the number of possible performance curves is very large. This is further complicated by the variability in the performance curves possible with different nozzle pressures. To simplify this situation, a unifying mathematical representation is needed.

As first presented by Gosline and O'Brien (1) and expanded on by Cunningham (2), it is possible to write a set of equations describing the performance of geometrically similar pumps. If the equations are written nondimensionally, they will apply to all sizes of pumps so long as the operating Reynolds' Numbers are close or sufficiently high that viscosity effects are negligible.

By considering the energy and momentum equations for the nozzle, suction passage, throat (mixing tube), and diffuser, the following equations can be derived (Refer to Fig. 4 and the glossary for nomenclature):

Nozzle Flow (BPD)

$$QN = 832\ AN\sqrt{\frac{PN-PS}{GN}} \tag{1}$$

Dimensionless Area Ratio

$$R = \frac{AN}{AT} \tag{2}$$

Dimensionless Mass Flow Ratio

$$M = \frac{QS \times GS}{QN \times GN} \tag{3}$$

Dimensionless Pressure Ratio

$$N = \frac{PD-PS}{PN-PD} \tag{4}$$

$$N = \frac{2R+(1-2R)\frac{M^2R^2}{(1-R)^2} - (1+KTD)R^2(1+M)^2}{(1+KN) - \text{Numerator}} \tag{5}$$

Efficiency

$$EFF = N \times M = \frac{(PD-PS)}{(PN-PD)}\ \frac{QS \times GS}{QN \times GN} \tag{6}$$

Cavitation Area (in^2)

$$ASM = (AT-AN) = \frac{QS}{691\sqrt{\frac{PS}{GS}}} \tag{7}$$

Equation (1), the nozzle flow rate, can be recognized as the expression for flow through an orifice. Equation (2) defines R as the ratio of the nozzle area to that of the throat. Equation (3) defines a dimensionless mass flow coefficient equal to the ratio of the production or suction flow rate to the nozzle flow rate times the ratio of the suction gradient to the nozzle fluid gradient. Equation (4) defines a dimensionless pressure ratio. Physically, it is the ratio of the pressure rise imparted to the produced fluid to the pressure lost by the power fluid in the pump. Equation (5), due to Cunningham (2), is a formulation for the dimensionless pressure of Equation (4) in terms of the area ratio, R, the mass flow ratio, M, and two loss coefficients, KN and KTD. These loss coefficients are experimentally determined and are similar to orifice and pipe friction loss coefficients. Equations (4) and (3) can be combined to give the efficiency, expressed in Equation (6). Since hydraulic power is the product of pressure differential times flow rate, Equation (6) is interpreted as the ratio of the power added to the produced fluid to the power lost from the power fluid. Equation (7) derived from the orifice flow equation for the annular production flow area at the entrance of the throat, defines the minimum flow area required to avoid cavitation if the suction flow rate is QS and is at a pressure of PS. This equation includes the assumption that the pressure at the entrance of the throat is zero at cavitation.

A representative set of dimensionless performance curves is shown in Fig. 3 for typical nozzle to throat area ratios of .50, .40, .30, .25, .20, and .15. The power fluid and produced fluid are of the same density. A nozzle loss coefficient of .03 was used, typical of a well shaped and smoothed design. A throat-diffuser loss coefficient of .20 was used. Lower values can be obtained in laboratory tests, but this conservative value compensates for average losses in routing the fluids through the rest of the pump and bottom hole assembly. The peak efficiencies of about 33% shown in Fig. 3 can be achieved with commercially available pumps producing typical well fluids at around a 700 BPD rate. Much larger or smaller pumps, or fluids of very low or high viscosity can result in pumps having somewhat higher or lower efficiencies respectively. Note that each area ratio curve has an associated efficiency curve, and that there is a most efficient ratio for a given value of the dimensionless mass flow ratio "M". These curves represent the type of non-cavitating performance obtainable from the jet pumps currently available from National, Kobe, and Guiberson. Operating under cavitating conditions will result in deviations from these curves.

APPROXIMATIONS FOR HANDLING GAS

The equations presented above are for liquids. Gas is present in many wells and affects pump performance. A rigorous treatment of the pumping of multiphase and compressible fluids is outside the scope of this paper. However, it has been found that simple but useful approximations can be made. Cunningham (2) found that if the free gas volume is added to the liquid volume as if it were liquid, pump performance follows the standard curves reasonably well. Equation (3) then becomes

$$M = \frac{QS + QG}{QN} \, \frac{GS}{GN} \tag{8}$$

A review of Standing's work (3) for a variety of bottom hole conditions results in an empirical correlation for the gas plus liquid phase volumes which, when substituted in Equation (8), gives

$$M = QS\left[\left(1 + 2.8\left(\frac{GOR}{PS}\right)^{1.2}\right)(1 - WC) + WC\right] \frac{GS}{QN \times GN} \tag{9}$$

A cavitation correction for gas is also required. Assuming choked flow into the throat annulus around the power fluid jet, the additional area required to pass the gas is

$$AG = \frac{QS(1 - WC)\,GOR}{24650\ PS} \tag{10}$$

Equation (7) considering gas then becomes

$$ASM = QS\left[\frac{1}{691}\sqrt{\frac{GS}{PS}} + \frac{(1 - WC)\,GOR}{24650\ PS}\right] \tag{11}$$

NOZZLE AND THROAT SIZES

Kobe, National, and Guiberson have different sizes and combinations of nozzles and throats. Kobe and National Production Systems increase the areas of nozzles and throats in a geometric progression. The Kobe factor is $10^{1/9} = 1.29155$ and the National factor is $4/\pi = 1.27324$. The progression of sizes from Guiberson is not geometric. The sizes offered by Guiberson cover a slightly larger range than those of Kobe and National. The sizes from each manufacturer are listed in Table 1.

The strict progression employed by National and Kobe establishes fixed area ratios between the nozzles and throats. A given nozzle matched with the same number throat will always give the same area ratio - .383 in the National system and .400 in the Kobe system. This is called the "A" ratio. Successively larger throats matched with a given nozzle give the "B", "C", "D" and "E" ratios. In the Kobe and National systems the size of a pump is designated by the nozzle size and ratio. Examples are 11-B or 6-A.

The various combinations of nozzles and throats in the Guiberson system cover the same basic range as the Kobe and National combinations. The actual ratios are listed in Table 2. In the Guiberson system, the nozzle and mixing tube (throat) sizes designate the size of a pump. An example is C-5. The annular areas of the Guiberson Jet Pumps used in cavitation calculations are also included in Table 2. The annular areas for the Kobe and National Jet Pumps are listed in Tables 3 and 4.

The most commonly employed area ratios fall between .400 and .235. Area ratios greater than .400 are sometimes used in very deep wells with high lifts, or when only very low operating pressures are available. Area ratios less than .235 are used in shallow wells or when very low bottom hole pressures require a large annular flow passage to avoid cavitation. Referring to Fig. 3, it can be seen that the performance curves for the higher area ratios show higher values of the dimensionless parameter "N" within their regions of maximum efficiency. Since "N" is a measure of the pressure rise in the produced fluid, the higher area ratios are suited for high net lifts, but this is achieved only with production rates substantially less than the power fluid rate ($M < 1.0$). The smaller area ratios develop less head, but may produce more fluid than is used for power fluid ($M > 1.0$).

CALCULATION SEQUENCE AND ADDITIONAL EQUATIONS

The calculator programs in the appendices use the following algorithm:

1. From the well data for production, QS, and pump intake pressure, PS, and the GOR, calculate the minimum annular area needed to avoid cavitation from Eqn (11).

2. From the tables of annular areas, select a nozzle and throat combination which has an annular area greater than ASM.

3. If it is desired, by calculating operating pressures, to evaluate different sizes to select an optimum, set a flag. If it is desired to plot curves at a constant operating pressure for a given size pump, do not set the flag.

4. Pick a surface operating pressure, usually between 2000 and 4000 psi, with higher pressures required at greater depths and with lower values of "R". Known available surface pump limitations may affect this choice.

5. Calculate the pressure at the nozzle. PN is the sum of the operating pressure plus the hydrostatic pressure in the tubing minus friction losses in the tubing.

$$PN = PT + GN \times D - PFN \tag{12}$$

The friction in annular or circular (tubing) sections can be determined from the following equation (4):

$$PF = \left[\frac{202 \times 10^{-8} L}{(D1-D2)(D1^2-D2^2)(D1/(D1-D2))^{.1}}\left(\frac{D1^2-D2^2}{D1-D2}\right)^{.21}\right]\left[\left(\frac{\mu}{G}\right)^{.21} G\right] Q^{1.79} \tag{13}$$

	Annular Flow	Tubing Flow
D1	Casing I.D.	Tubing I.D.
D2	Tubing O.D.	0

The expression within the first set of brackets is a constant for a given tubing string or annular flow passage. The expression in the second set of brackets is a constant for the power fluid losses, but not for the production return conduit since it will contain a variable mix of power fluid and production.

6. Determine the power fluid rate from Equation (1) and the selected nozzle size.

7. Determine the return flow rate.

$$QD = QN + QS \tag{14}$$

8. Determine the production (pump suction) gradient.

$$GS = (GW \times WC) + (1 - WC)GO \tag{15}$$

9. Determine the return flow fluid gradient.

$$GD = \frac{(GS \times QS) + (GN \times QN)}{QD} \tag{16}$$

10. Calculate the return flow water cut.

$$WCD = \frac{QS \times WC}{QD} \quad \text{Oil Power Fluid} \tag{17}$$

$$WCD = \frac{QN + (QS \times WC)}{QD} \quad \text{Water Power Fluid} \tag{18}$$

11. Calculate the return flow gas liquid ratio.

$$GLR = \frac{QS(1-WC)GOR}{QD} \tag{19}$$

12. If the GLR is greater than 10, it is recommended to use a vertical multiphase flow pressure gradient correlation to determine the pump discharge pressure using values from Equations (14) through (19). Gas lift charts can be used. Then go to Step 15.

13. If the GLR is less than 10, determine the return flow liquid viscosity for calculating friction losses.

$$\mu_D = WCD \times \mu_W + (1 - WCD)\mu_O \qquad (20)$$

This weighted average equation assumes that if oil is used for power fluid, it has the same viscosity as the produced oil and that no emulsions are formed.

14. Determine the pump discharge pressure. PD is the sum of the hydrostatic pressure in the return conduit, the friction losses, and the wellhead back pressure.

$$PD = (GD \times D) + PFD + PWH \qquad (21)$$

15. Calculate "M" from Equation (9).

16. Calculate "N" from Equation (5) for the value of "R" selected, using the value of "M" from Step 15.

17. Compare the current value of N with the previous value. If the difference is less than 1/2%, iteration is complete and go to Step 20 (flag set) or Step 21 (flag not set). Otherwise, go to Step 18. Three to 10 iterations are normally required. The 1/2% convergence criterion leads to answers that are reproducible to within about ± 15 psi.

18. If the flag is set, calculate a new nozzle pressure from equation (4).

$$PN = \frac{PD - PS}{N} + PD \qquad (22)$$

Then go to Step 6.

19. If the flag is not set, calculate a new pump intake pressure from equation (4).

$$PS = PD - N(PN - PD) \qquad (23)$$

Then go to Step 5.

20. Determine the new surface operating (triplex) pressure.

$$PT = PN - (GN \times D) + PNF \qquad (24)$$

21. Calculate the maximum non-cavitating flow.

$$QSC = QS\left(\frac{AT - AN}{ASM}\right) \qquad (25)$$

22. Calculate the triplex horsepower, assuming 90% efficiency.

$$HP = \frac{QN \times PT}{52910} \qquad (26)$$

23. Display Power Fluid Pressure, PT
Power Fluid Rate, QN
Triplex Horsepower, HP
Cavitation Flow Rate, QSC
Production Rate, QS
Pump Intake Pressure, PS

24. For a new size pump, go to Step 1, inputting the new size at Step 2, and set the flag at Step 3. To calculate a performance chart for a chosen size, go to Step 1, inputting a new production rate, and do not set the flag (or remove it if it is already set) at Step 3. With this option, a number of points can be calculated for a given triplex pressure.

PERFORMANCE CHARTS

Kobe created the format shown in Fig. 6, and has the chart drawn by a computer driven plotter. Guiberson employs a similar procedure (Fig. 8). Referring to Fig. 6, enter the chart on the horizontal axis at a particular production rate (2040 BPD). Read upward to the appropriate pump intake pressure (1500 PSI) identified by the curves rising to the right. Read to the left to the vertical axis to obtain the power fluid rate (2695 BPD). The triplex pressure is obtained by interpolating between the power fluid pressure curves falling to the right (3230 PSI). The IPR curve can be superimposed on the chart.

National Production Systems presents pump performance data in the format shown in Fig. 10. Here a normal IPR curve is drawn and the pump performance curves are superimposed on it. Since this format is simpler for hand plotting and since there is a tendency in the current literature to present artificial lift performance curves in this manner, it is suggested for use with the programs in the appendices.

To interpret Fig. 10 enter the chart on the horizontal axis at a particular production rate (205 BPD). Read upward to the appropriate pump intake pressure (1550 PSI). The power fluid pressure can be read by interpolating between the curves (3200 PSI). Power fluid rates are obtained by interpolating between the values listed (approximately 803 BPD).

USE OF THE CALCULATOR PROGRAMS

Instructions for the use of the calculator programs are given in Appendix 1 (TI-59) and Appendix 2 (HP-41C). Program listings are also included.

As an example, consider the following data for a hypothetical well.

DEPTH: 5000 ft
TBG LENGTH: 6000 ft
TBG OD: 2.375 in
TBG ID: 1.995 in
RETURN ID: 4.892 in
WELL HEAD PRESS: 100 psi
PWR GRAD: .353 psi/ft

PROD OIL GRAD: .353 psi/ft
WATER GRAD: .446 psi/ft
OIL VISC: 2.5 cp
GOR: 0 scf/BBL
WATER CUT: .30
PRODUCTION: 500 B/D
BOTTOM HOLE PRESS: 1000 psi

The calculator program indicates a minimum suction area (throat annulus area) of .0141 in^2 (sample TI-59 output tapes are included in Table 5). Referring to Tables 2, 3, and 4, note that above a certain size nozzle, all combinations have adequate area. Below this size, only certain ratios have adequate area. Generally, the smallest pumps that will satisfy the throat annulus area requirement are candidates to consider. Usually, considering three different ratios will clarify the tradeoffs between power fluid rate, operating pressure, and required horsepower, and enable selection of an optimum size.

Likely candidates from the Guiberson options (Table 2) are A-3, B-3, and B-4. Possibilities from Kobe include 4-C, 5-B, and 6-B (Table 3) and the same size designations from National (Table 4). For this example, the Guiberson sizes will be evaluated. The calculator program was run with the Flag Set. The following results were obtained.

Size	R	PT	QN	HP	QSC	QS	PS
A-3	.23	3284	489	30.4	659	500	1000
B-3	.40	2517	761	36.2	517	500	1000
B-4	.30	2278	733	31.6	775	500	1000

In this case, the A-3 combination would produce the desired 500 BPD with the least horsepower, but at the highest operating pressure. The calculator program was the run for the A-3 combination with the Flag Not Set and the following results were obtained.

Size	R	PT	QN	HP	QSC	QS	PS
A-3	.23	3000	462	26.2	703	500	1139
		3000	449	25.5	763	600	1340
		3000	475	27.0	636	400	934
		3500	507	33.6	627	500	907
		3500	494	32.7	698	600	1124
		3500	519	34.4	547	400	689

These data are plotted in Fig. 5. A line indicating a PI of 1.0 is also plotted through the target production point. The operating pressure curves are plotted over a range of intake pressures which includes the target flowing bottom hole pressure. This allows for some uncertainty in the input data and shows the pump performance over a range of conditions. Note that the maximum production obtainable with this pump is approximately 620 BPD at the intersection of the PI line with the cavitation line. Extrapolation indicates this would occur at an operating pressure of about 4100 psi. Power fluid rates are indicated at several points near the desired production rate.

FIELD RESULTS

Well data supplied by National Production Systems is listed in Table 6. This data was input into a jet pump simulation computer program for a 6-A nozzle and throat combination, and the results are plotted in Fig. 10. The actual well production varied between 195 BPD and 205 BPD during test. A bottom hole pressure recorder showed pump intake pressures (PS) starting at about 1805 psi and declining to a stable 1550 psi during the test. The surface operating pressure varied between 3150 and 3200 psi. The computer plot indicates that 206 BPD should be produced at a surface operating pressure (PT) of 3200 psi.

The calculator program in the appendices was run for the same data. The calculator generated 3200 psi line is shown as a dotted line with circled points in Fig. 10. Since gas was present, gas lift charts were used to estimate the pump discharge pressure between 3150 and 3300 psi over the range plotted.

Both the computer program and the calculator program agree very well with the test data, with the calculator routine being slightly optimistic in predicting 215 BPD production at 3200 psi operating pressure. The calculator routine also predicts a larger flow rate possible at cavitation. Both these effects are due to the approximations made in handling the gas volumes at downhole conditions. Gas effects are the most frequent cause of discrepancies between actual and predicted performance. Discrepancies of ± 10% are not uncommon.

Well data supplied by Kobe, Inc. is listed at the top of Fig. 6, which is the computer plot of the calculations for an 11-B nozzle and throat combination. Recent bottom hole pressure information is not available, but the well is producing 2040 BFPD at a surface operating pressure of 3300 psi. The power fluid rate is 2695 BPD, indicating a pump intake pressure of about 1500 psi. Note that the computer chart predicts an operating pressure of 3230 psi, agreeing very closely with the actual value of 3300 psi. In 1979, the well's PI was calculated at 2.65. Such a PI line has been constructed on Fig. 6.

A similar PI line has been drawn on Fig. 7, and the calculator program has been used to calculate operating pressure lines and a cavitation line. The field data point is circled. Note that the calculator program predicts an operating pressure (PT) of 3800 psi compared to the actual and computer predicted 3300 psi. At 3300 psi, the calculator program predicts about 1825 BPD production instead of the observed 2040 BPD. The calculator cavitation curve closely matches the upper boundary of the Kobe cavitation zone. The lower "potential damage" cavitation curve on the Kobe computer plot is not modelled in the calculator program.

Again, gas effects are not modeled in as sophisticated a manner in the calculator program as in the computer program. Also, this case involves a large pump, an 11-B nozzle-throat combination in a 3" pump, and better efficiencies can be expected. This is particularly true with low viscosity fluids, as is the case here, because of the resulting high Reynolds' Numbers. This effect is not included in the model used in the calculator program. This same nozzle and throat in a 2-1/2" pump would probably perform closer to the calculator predictions due to greater friction losses within the pump passages.

Guiberson supplied well data are presented in Table 7. These data were used to generate the map of pump performance shown in Fig. 8. The calculations were for a C-5 nozzle and mixing tube (throat). Well production tests varied from 690 BPD to 780 BPD with an average of 700 BPD. The static fluid level was measured 2000 ft from the surface and the well was reported to have a 1700 psi producing bottom hole pressure at 500 BPD. The IPR curve superimposed on the map indicates an operating pressure of 2800 psi at a 700 BPD production rate and 1566 psi producing bottom hole pressure. The actual operating pressure started at 2700 psi and is currently at 2800 psi. The exact volume of power fluid is unknown since some of the Triplex output is being bypassed. The maximum Triplex output is 1190 BPD, so the power fluid volume of 955 BPD indicated by the computer plot is a good prediction of the amount actually used.

The calculator program was run for this well and the results are presented in Fig. 9. Since gas was produced, flowing gradient curves were used to input a pump discharge pressure of 2485 psi. At the current conditions, the calculator program predicts an operating pressure of 2850 psi and a power fluid volume of 996 BPD. This closely matches both the actual well data and the computer calculations.

The cavitation line on the computer plot is generated without gas effects in this case, since the gas volumes present will greatly reduce any cavitation damage.

DISCUSSION AND CONCLUSIONS

The procedures presented above can be used to make reasonable predictions about the performance of jet pumps in oil wells. Employing the calculator programs in the mode which calculates a surface operating pressure and power fluid rate to produce a targeted production rate (Flag set) allows a comparison of different sizes of nozzles and throats to minimize the horsepower requirements or to match existing power fluid supply limitations. Using the calculator programs in the constant operating pressure mode (Flag not set) enables calculation of operating pressure curves which can be drawn on an IPR plot. Such a plot allows a quick determination of operational characteristics under different bottom hole conditions. This includes the prediction of the intersection of the well's IPR curve with the pump's cavitation limit.

Simplifying assumptions in the performance equations and in correlations for liquid and gas properties have been made to fit the algorithm into the memory limitations of hand held programmable calculators. The well's IPR curve is often not well known, and the gas production of an individual well may be uncertain. Jet Pump performance is strongly affected by the pump intake pressure (determined by the IPR curve) and by the pump discharge pressure (significantly determined by the gas oil ratio). For every psi error in the pump intake pressure or pump discharge pressure, the effect on the surface operating pressure will be from three to five psi if the same production rate is to be obtained. Higher discharge pressures or lower pump intake pressures require higher operating pressures. This multiplier effect is greatest with the larger throats (low values of R). Fluid friction losses through the passages of the particular downhole completion hardware can affect these pressures as well.

Even when accurate well data are available, the performance predictions may not always match field performance. When the volume of free gas at producing bottom hole conditions is very large, performance will suffer beyond the degree predicted by the equations. Current jet pump designs have been optimized for liquid production, not for pumping gas. Accuracy of prediction begins to suffer at around five parts of gas to one part liquid, and at 90% gas the predictions are very questionable.

The performance of jet pumps with fluids of high viscosity is not modelled in the calculator programs. Heavy crudes with viscosities above about 1000 cp will cause significant deviations from predictions unless produced water is the dominant phase. Oil power fluids of less than about 22 API will also introduce losses that are not properly modelled.

Generally, the calculator algorithm presented here should tend to produce predictions in which any deviations are small or are on the conservative side. Using these techniques, production engineers can evaluate jet pumps for their artificial lift needs. If jet pumping looks reasonable, as it will in many wells, the suppliers can be contacted for confirming calculations and the actual surface and downhole pump hardware recommended for the application.

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GLOSSARY

AN	Flow area of the nozzle (in^2).
AS	Throat annulus area (AT-AN) (in^2).
ASM	Minimum throat annulus flow area to avoid cavitation (in^2).
AT	Flow area of the throat (in^2).
D	Vertical depth of well (ft).
D1	Inside diameter of tubing or casing (in).
D2	OD of inner tubing in annular flow (in).
Eff	Jet pump efficiency.
GD	Gradient of mixed power fluid and produced fluid returning to surface (psi/ft).
GLR	Gas-liquid ratio in return flow to surface (scf/BBL).
GN	Gradient of power fluid passing through nozzle (psi/ft).
GO	Gradient of produced oil (psi/ft).
GOR	Gas-oil ratio (scf/BBL).
GS	Gradient of well produced fluid (psi/ft).
GW	Gradient of water (psi/ft).
HP	Horsepower.
KN	Nozzle loss coefficient.
KTD	Throat-diffuser loss coefficient.
L	Tubing length (ft).
M	Dimensionless mass flow ratio.
N	Dimensionless pressure recovery ratio.
PD	Pump discharge pressure (psi).
PF	Friction loss in tubing (psi/ft).
PFN	Friction loss in power fluid tubing (psi/ft).
PFD	Friction loss in return conduit (psi/ft).
PN	Pressure at the nozzle entrance (psi).
PS	Pump suction pressure (producing bottom hole pressure) (psi).
PT	Surface operating pressure (triplex pressure) (psi).
PWH	Flow line pressure at the wellhead (psi).
QD	Flow rate from pump discharge (BPD).
QG	Flow rate of gas through pump (BPD).
QN	Flow rate through the nozzle (BPD).
QS	Flow rate to pump suction (production flow rate) (BPD).
QSC	Maximum non-cavitating pump suction flow rate (BPD).
R	Dimensionless ratio of nozzle area to throat area.
WC	Production water cut (50% water cut is entered as .50).
WCD	Water cut in return flow to surface.
μ_o	Viscosity of return fluids (cp).
μ_o	Viscosity of oil (cp).
μ_w	Viscosity of water (cp).

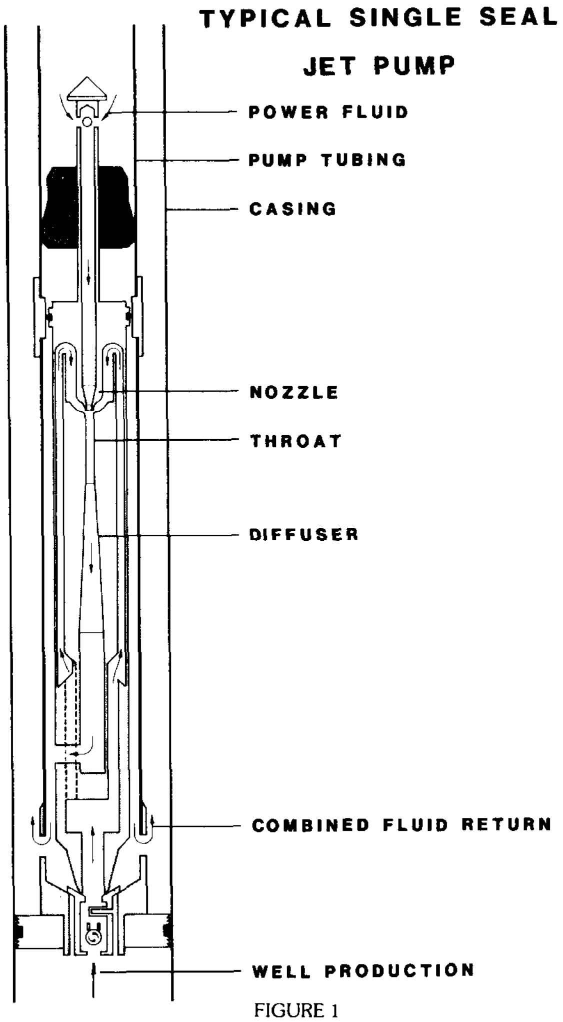


FIGURE 1

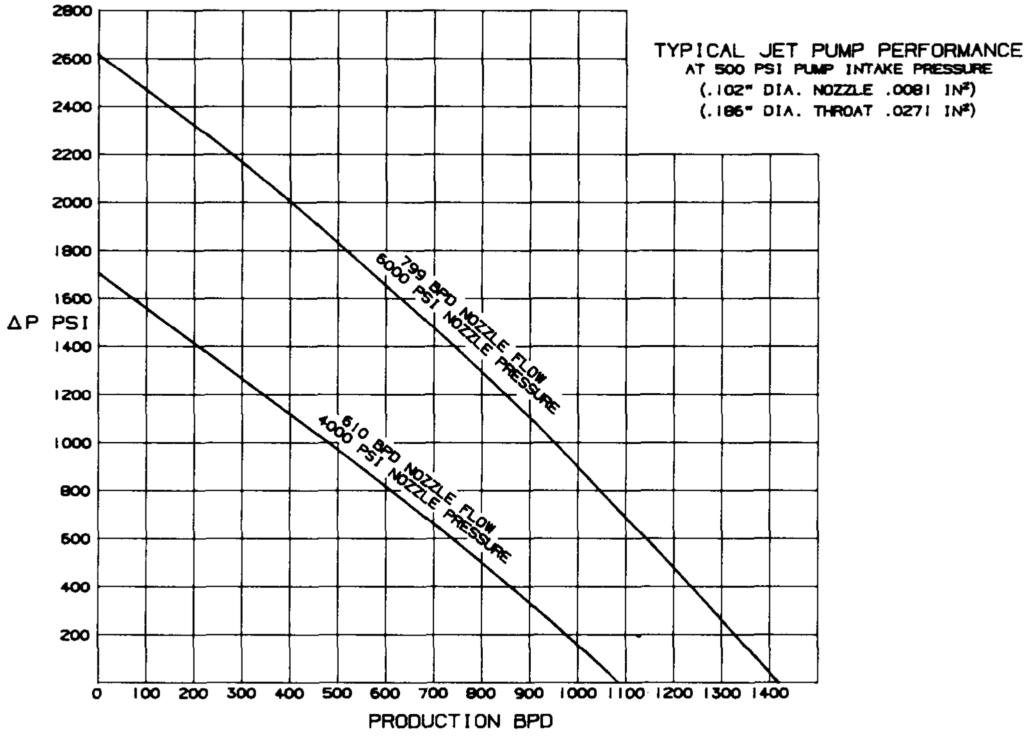


FIGURE 2

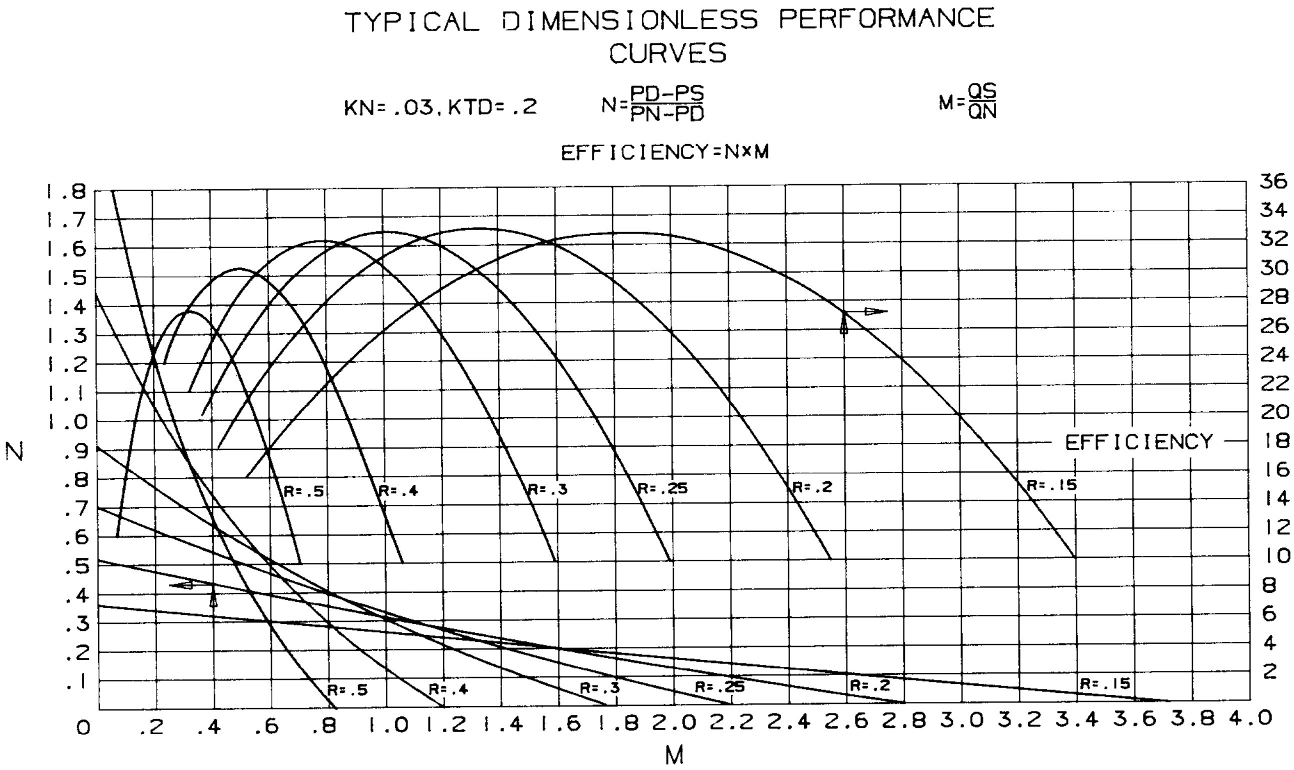


FIGURE 3

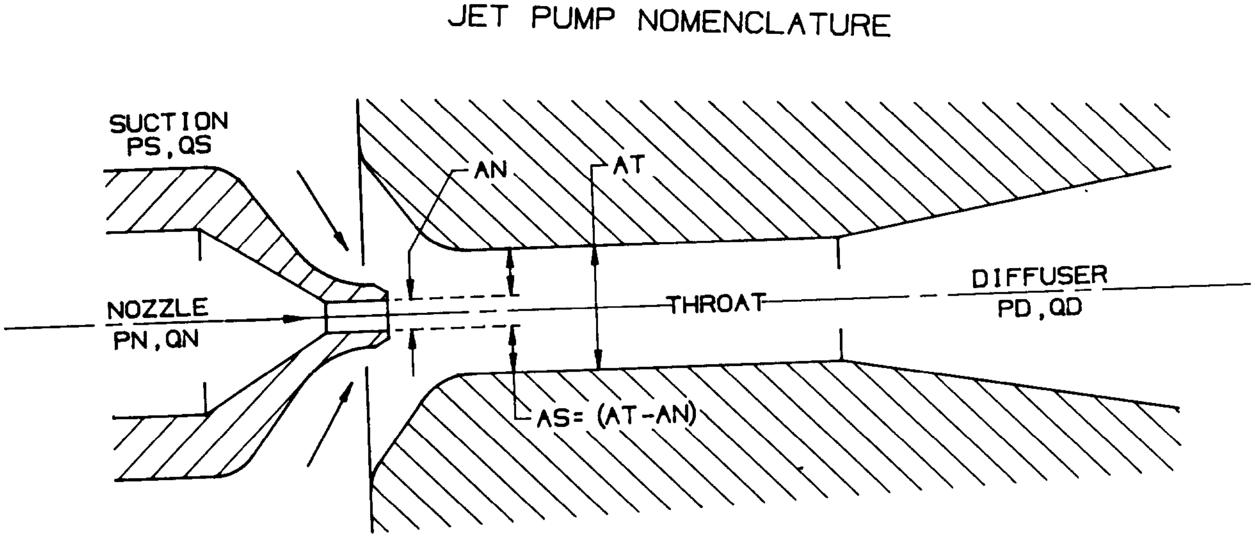


FIGURE 4

A-3 2" JET PUMP PRODUCTION UNIT PERFORMANCE

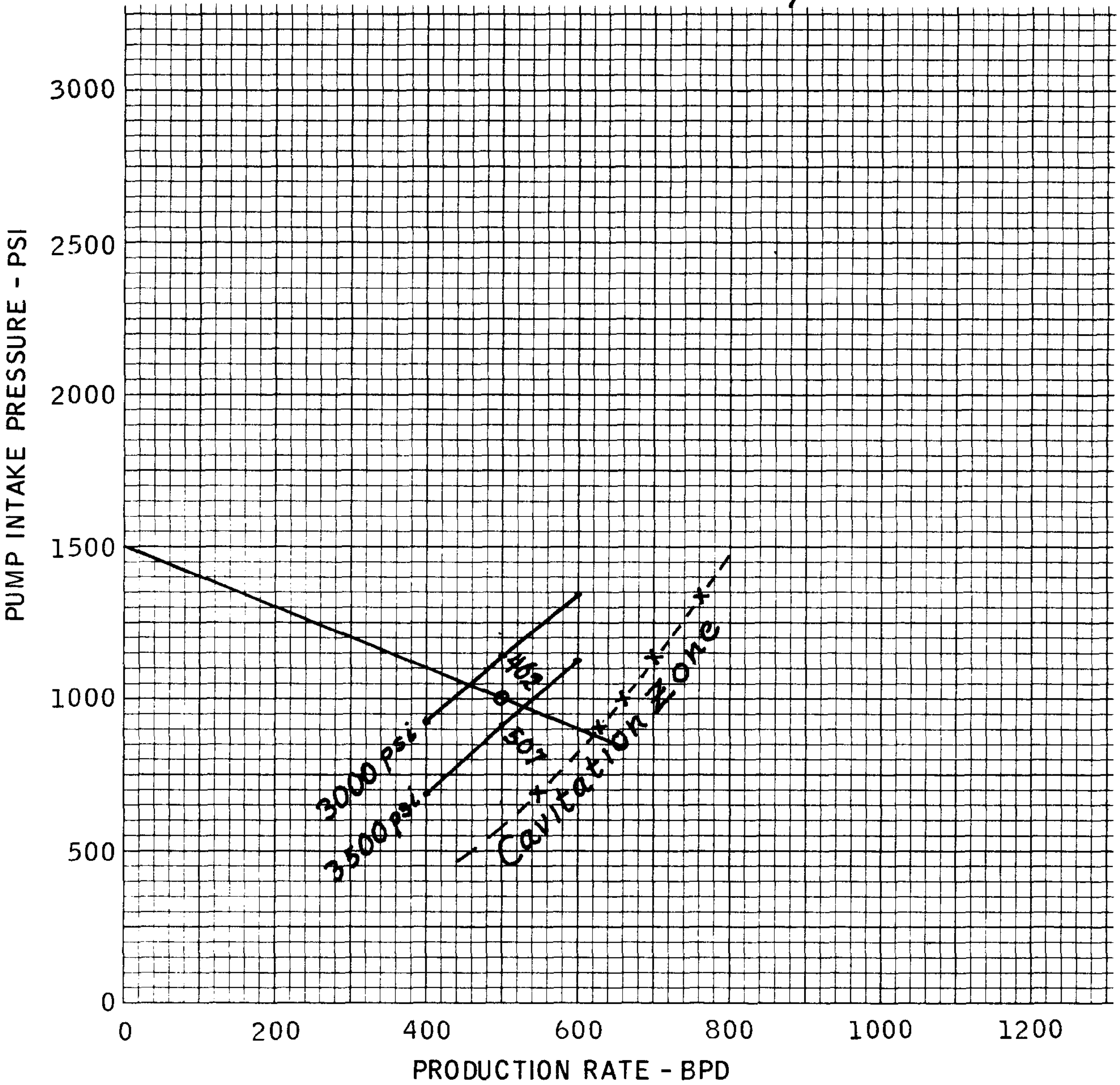
DEPTH OF PUMP 5000 FT. TUBULARS 2 3/8 x 5 1/2

OIL 42 °API .8155 S.G. WATER 1.03 S.G. 30 %

GAS 0 GOR SCF/BBL POWER FLUID Oil

WELLHEAD FLOW LINE 100 PSI DATE ______ BY ______

Calculator Prediction for Example



NOTE - NUMBERS ADJACENT TO CURVES ARE POWER FLUID - BPD
- JET PUMP OPERATION MUST BE ABOVE & LEFT OF CAVITATION LINE

FIGURE 5

```
SHORT COURSE                                  PRODUCTION OIL API       42.100
LUBBOCK                                       POWER FL. OIL            42.100
DEMO.                                         PIP TARGET,PSI            1500.
DEMO.                                         WELL HEAD TEMP, F           90.
DATE                  2-2-83                  B. H. TEMP, F              184.
PROD TARG.,B/D            2000.               VAPOR PRESSURE, PSI          0.
PUMP SIZE    3        X11-B                   VERT DEPTH, FT.           7000.
G.O.R.                    1250.               TBG LENGTH, FT.           7000.
GAS S.G.                   .908               CASE I.D., IN.            6.094
PLOT NO.          1        9125               TUBING O.D., IN.          2.375
SEPARATOR PRESS.,PSI        40.               COUPLING O.D., IN.        3.063
FLOW LINE PRESS.,PSI        75.               TUBING I.D., IN.          1.995
WATER CUT                   98.               UPSTRING  7 X 2-3/8
PRODUCTION H20 S.G.       1.030               DOWNSTRING  2-3/8 FIXED
```

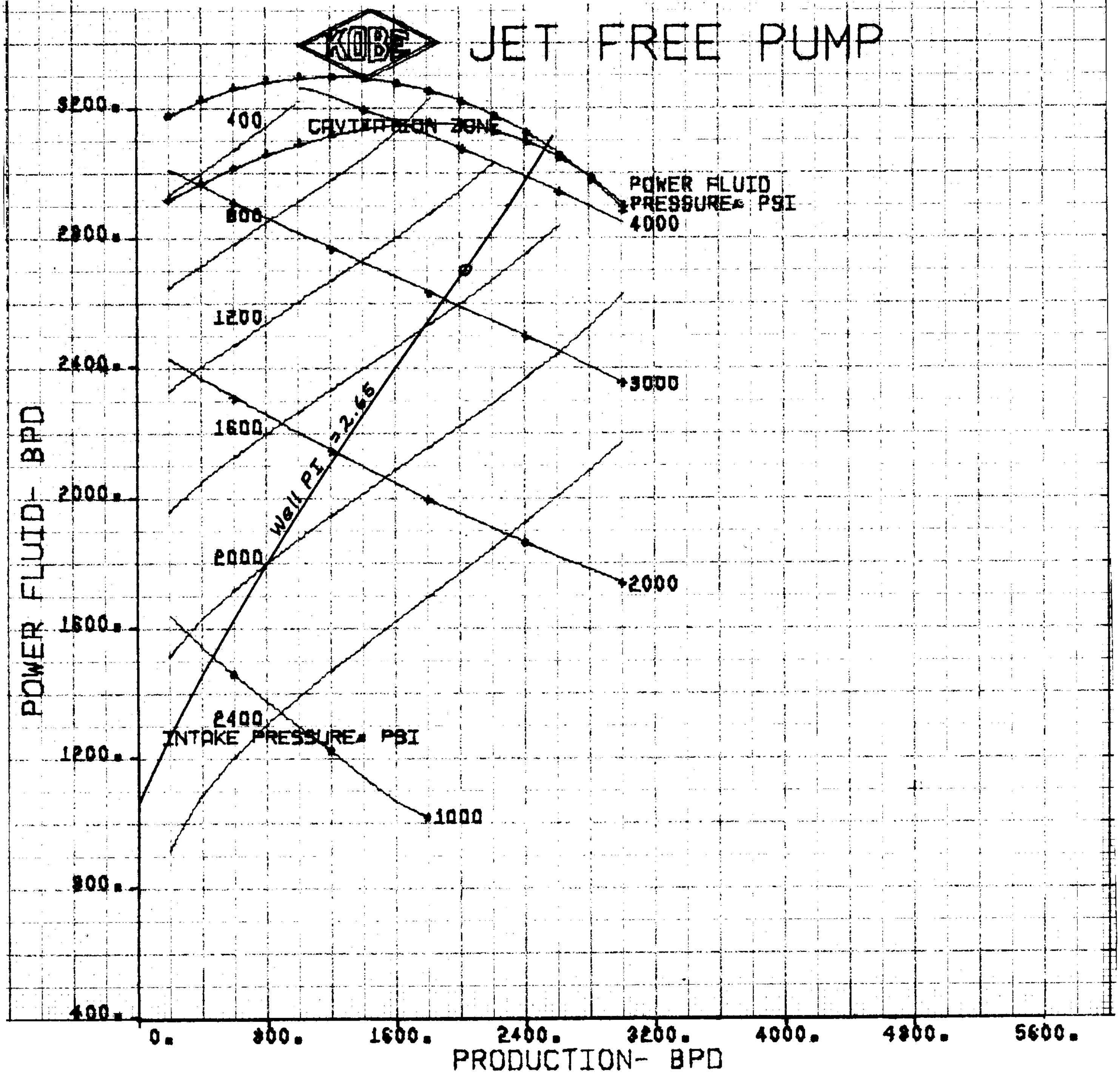


FIGURE 6

11-B 3" JET PUMP PRODUCTION UNIT PERFORMANCE

DEPTH OF PUMP 7000 FT.

TUBULARS 2 3/8 x 7" Fixed

OIL 42.1 °API .8151 S.G.

WATER 1.03 S.G. 98 %

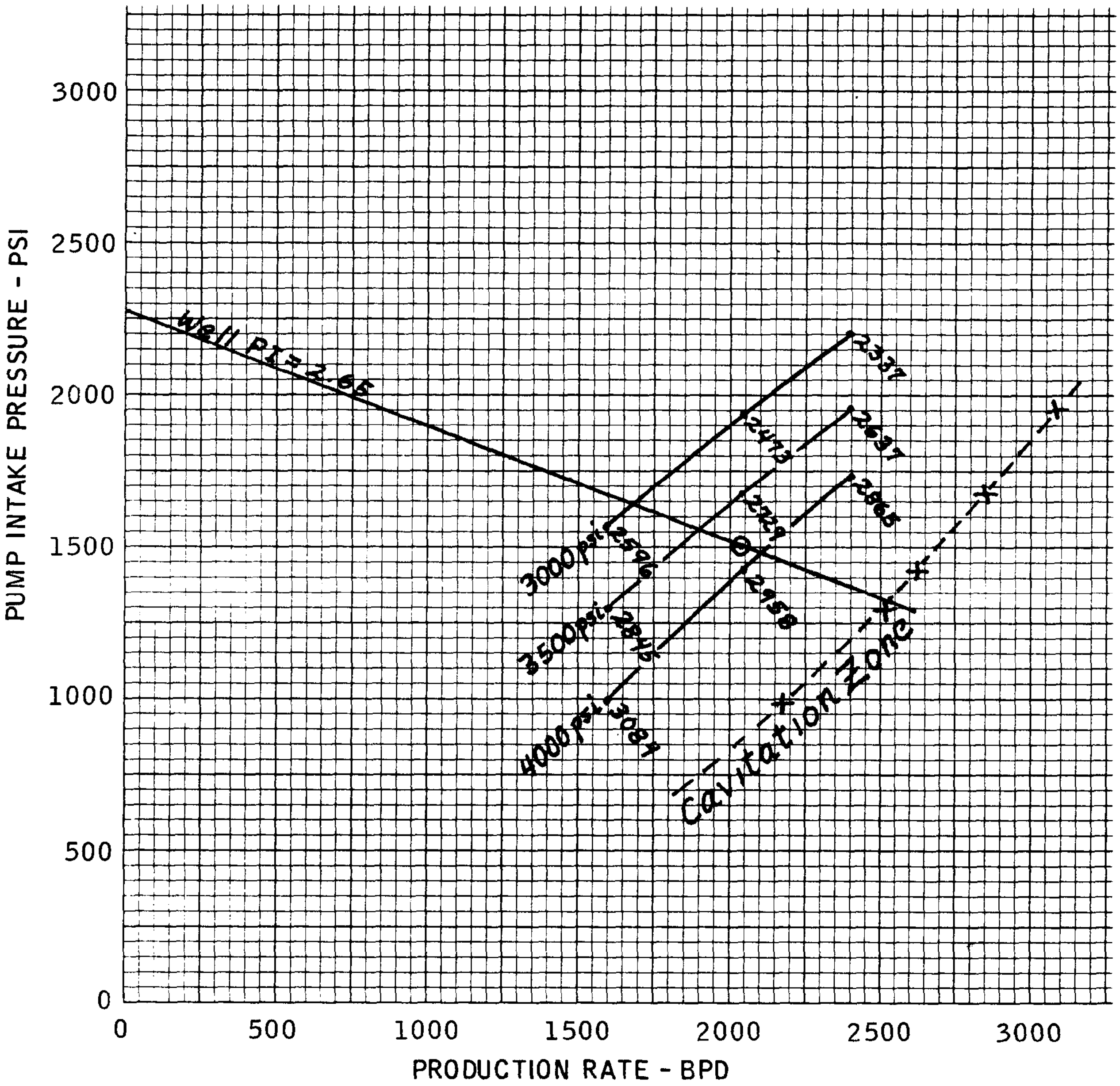
GAS 1250 GOR SCF/BBL

POWER FLUID Oil

WELLHEAD FLOW LINE 75 PSI

DATE ____ BY ____

Calculator Prediction for Kobe Well



NOTE - NUMBERS ADJACENT TO CURVES ARE POWER FLUID - BPD
- JET PUMP OPERATION MUST BE ABOVE & LEFT OF CAVITATION LINE

FIGURE 7

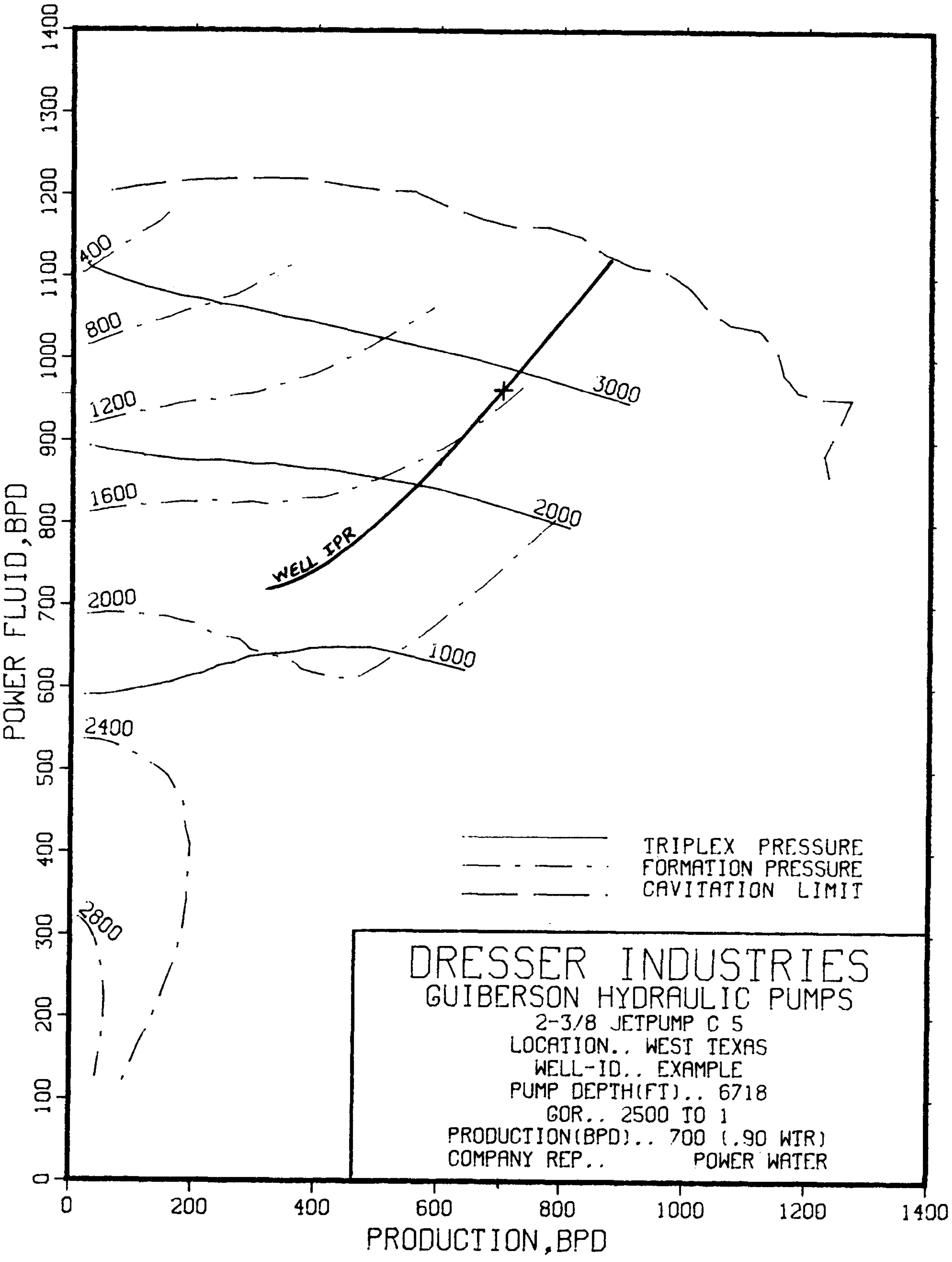

POWER FLUID,BPD
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
PRODUCTION,BPD
0
200
400
600
800
1000
1200
1400
400
800
1200
1600
2000
2400
2800
3000
2000
1000
WELL IPR
TRIPLEX PRESSURE
FORMATION PRESSURE
CAVITATION LIMIT
DRESSER INDUSTRIES
GUIBERSON HYDRAULIC PUMPS
2-3/8 JETPUMP C 5
LOCATION.. WEST TEXAS
WELL-ID.. EXAMPLE
PUMP DEPTH(FT).. 6718
GOR.. 2500 TO 1
PRODUCTION(BPD).. 700 (.90 WTR)
COMPANY REP.. POWER WATER

FIGURE 8

C-5 2" JET PUMP PRODUCTION UNIT PERFORMANCE

DEPTH OF PUMP 6718 FT.

TUBULARS 2 3/8 x 4 1/2"

OIL 52 °API .771 S.G.

WATER 1.05 S.G. 90 %

GAS 2500 GOR SCF/BBL

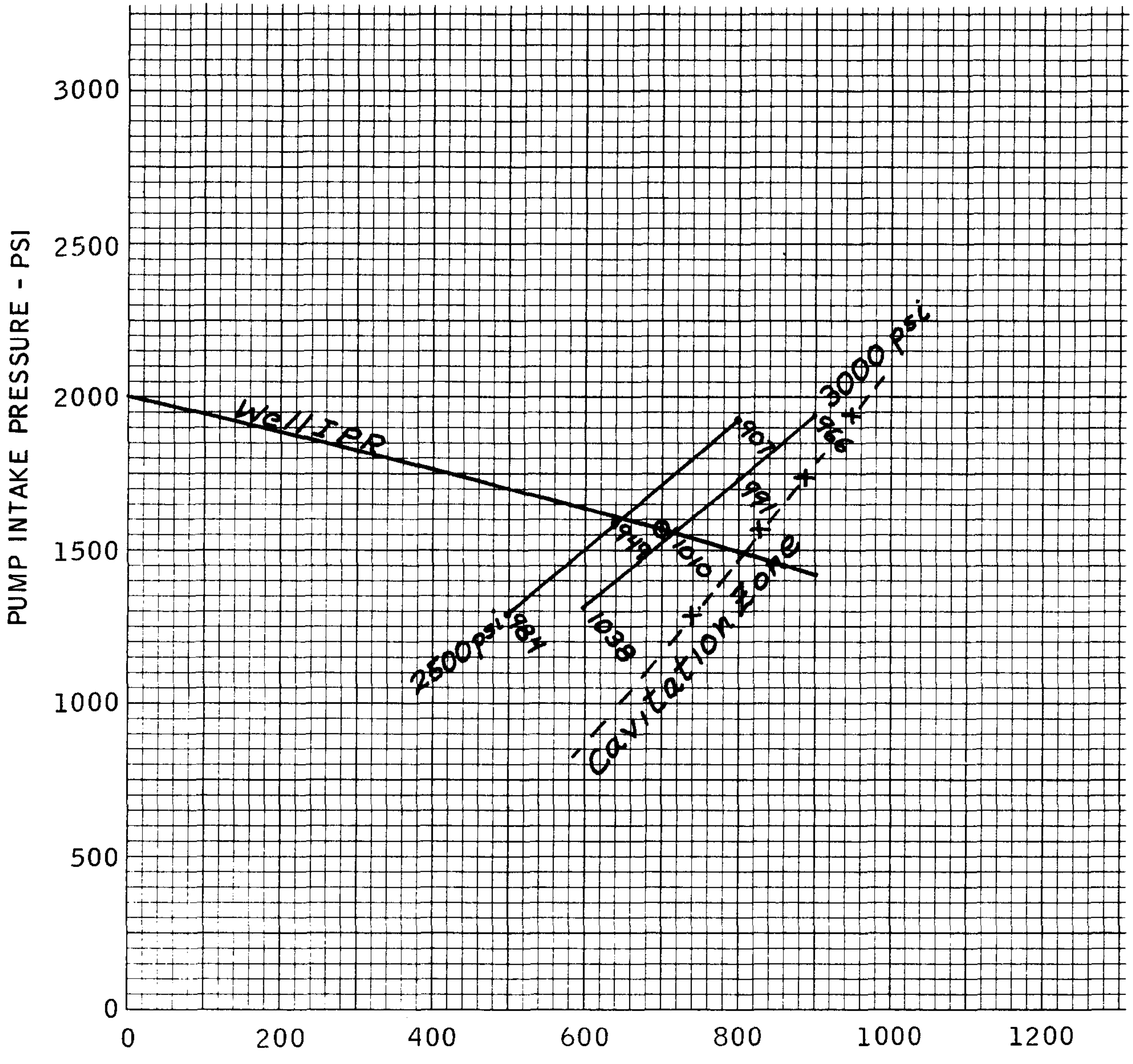
POWER FLUID Water

WELLHEAD FLOW LINE 100 PSI

DATE

BY

Calculator Prediction for Guiberson Well



NOTE - NUMBERS ADJACENT TO CURVES ARE POWER FLUID - BPD

- JET PUMP OPERATION MUST BE ABOVE & LEFT OF CAVITATION LINE

FIGURE 9

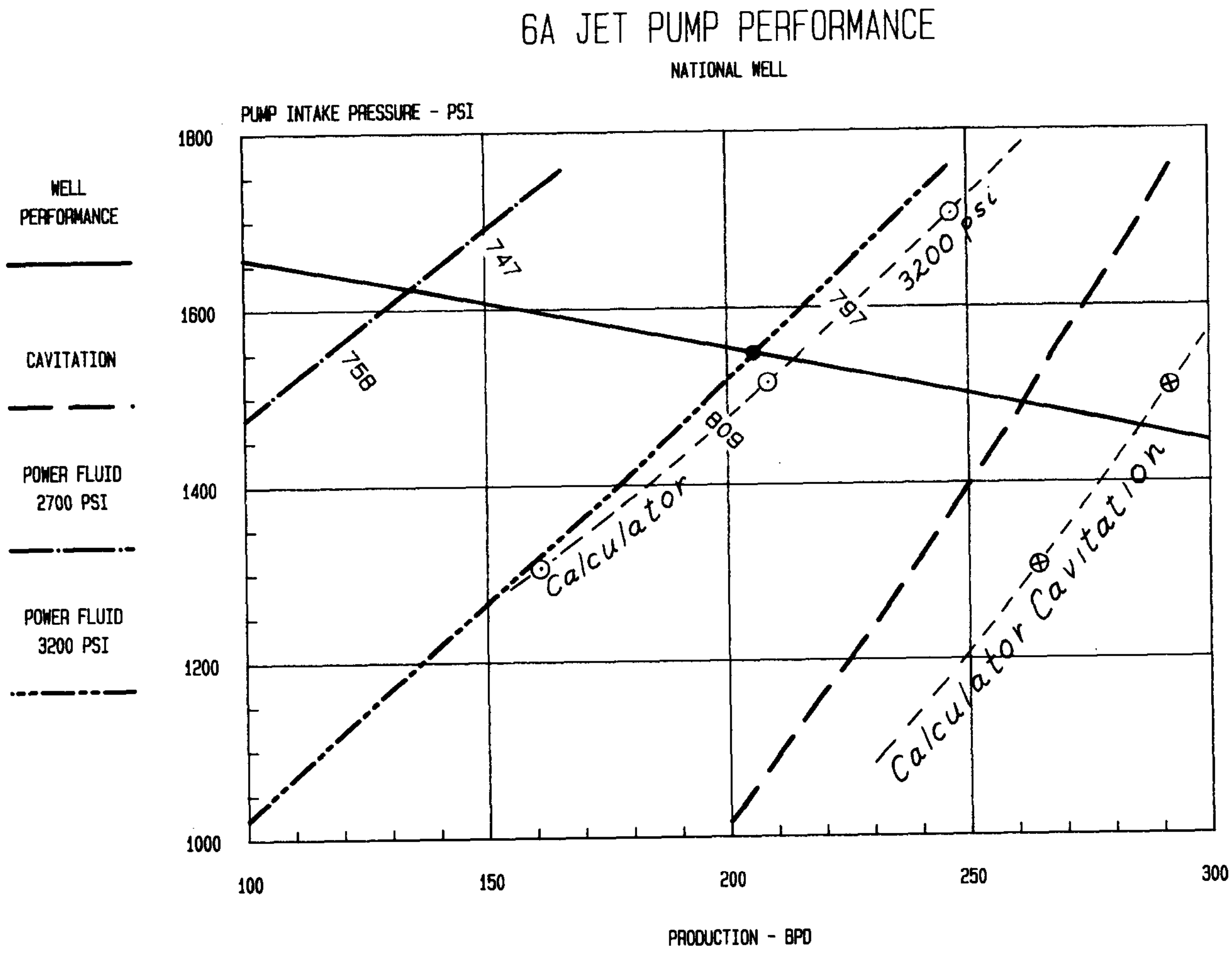

6A JET PUMP PERFORMANCE
NATIONAL WELL
PUMP INTAKE PRESSURE - PSI
1800
1600
1400
1200
1000
100
150
200
250
300
PRODUCTION - BPD
WELL PERFORMANCE
CAVITATION
POWER FLUID 2700 PSI
POWER FLUID 3200 PSI
747
758
797
809
3200 psi
Calculator
Calculator Cavitation

FIGURE 10

TITLE APPENDIX 1 JET PUMP DATA PAGE 1 OF 1

TI Programmable Program Record

PROGRAMMER ____________ DATE ________

Partitioning (Op 17) 7 1 92 9 Library Module ____________ Printer PC 100A Cards 1,2,3

PROGRAM DESCRIPTION

1. Input and storage of well data.
2. Calculation and storage of GS, friction constant for return, friction constant for power fluid, (1-Water Cut)
3. Initialize Storage Register 25 as 0.40

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS	DISPLAY
1	Partition to 719.29	3 OP 17	R/S	719.29
2	Cards 1,2,3 (CLR before each)			1,2,3
3	Start		A	DATA
4	Enter or Accept	Depth	R/S	Depth
5	"	Tbg Length	"	Tbg Length
6	"	Tbg ID	"	Tbg ID
7	" (0 for parallel rtn)	Tbg OD	"	Tbg OD
8	"	Rtn ID	"	Rtn ID
9	"	Flowline Press	"	Flowline Press
10	"	Pwr Grad	"	Pwr Grad
11	"	Oil Grad	"	Oil Grad
12	"	Wtr Grad	"	Wtr Grad
13	"	Oil Visc	"	Oil Visc
14	"	GOR	"	GOR
15	"	Water Cut	"	Water Cut
16	Calculate after entering Water Cut			0
17	Load "Jet Pump Calculation" if data correct. Return to 3 for corrections.			

USER DEFINED KEYS	
A	Start
B	
C	
D	
E	
A'	
B'	
C'	
D'	
E'	

DATA REGISTERS (INV [illegible])	
0 GS	10 Oil Visc (μ_o)
1 Depth (D)	11 GOR
2 Tbg Length (L)	12 Water Cut (WC)
3 Tbg ID	13 D1P
4 Tbg OD	14 D2
5 Rtn ID	15 (D1-D2)
6 Flowline Press	16 $(D1^2 - D2^2)$
7 Pwr Grad (GN)	17 Fric Const Rtn
8 Oil Grad (GO)	18 Fric Const Pwr
9 Water Grad(GW)	19 (1-WC)

LABELS (Op 08)

INV __	lnx __	CE __	CLR __	x⇌t __	x^2 __
√x __	1/x __	STO __	RCL __	SUM __	y^x __
EE __	(__	) __	÷ __	GTO __	X __
SBR __	− __	RST __	+ __	R/S __	• __
+/− __	= __	CLR __	INV __	log __	CP __
[illegible] __	[illegible] __	P→R __	[illegible] __	[illegible] __	CMs __
[illegible] __	[illegible] __	|x| __	[illegible] __	[illegible] __	[illegible] __
Deg __	[illegible] __	x [illegible] __	[illegible] __	[illegible] __	[illegible] __
[illegible] __	x [illegible] __	Σ+ __	x __	[illegible] __	[illegible] __
[illegible] __	DMS __	π __	[illegible] __	[illegible] __	[illegible] __
Adv __	[illegible] __				

FLAGS									
0	1	2	3	4	5	6	7	8	9

1014966-1

FIGURE 11

TITLE APPENDIX 1 JET CALCULATION PAGE 1 OF 1 **TI Programmable**

PROGRAMMER ____________ DATE ________ **Program Record**

Partitioning (Op 17) 7,19.2,9 Library Module ____________ Printer PC 100A Cards 1,2,3

PROGRAM DESCRIPTION

1. Calculates Jet Pump Performance
   a. With Flag 1 Set (Step 8), Operating Pressure will be varied to find a solution.
   b. With Flag 1 Not Set (Step 8), Pump Suction Pressure will be varied to find a solution at a given Operating Pressure.
   c. If the Gas-Liquid Ratio in the return is greater than 10, a pump discharge pressure must be input (Step 10).

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Cards 1,2,3 (CLR before each)					1,2,3
2	Start		A			JET
3	Enter or Accept	Prod. Rate	R/S			QS
4	Enter or Accept	Suct. Press	R/S			PS
5	Display Minimum Suction Area (in^2)		R/S			ASM
6	Enter or Accept Nozzle Area (in^2)	Noz. Area	R/S			AN
7	Enter or Accept Throat Area (in^2)	Tht. Area	R/S			AT
8	Set Flag 1 for operating pressure required at given Prod. & PIP. Do not set Flag 1 for constant operating pressure.		St	Flag	1	FLAG?
9	Enter or Accept operating Pressure	Op. Press.	R/S			PT
10	If GLR in return is greater than 10, Print GLR,WC,GD,QD. Enter PD	Dis Press	R/S			PD?
11	Prints solution: Operating Pressure, Nozzle Flow Rate, Horsepower, Max. Noncavitating Flow, Production Rate, Pump Suction Pressure. Then Step 2.					PT,QN,HP,QSC, QS, PS

USER DEFINED KEYS		DATA REGISTERS (INV [illegible])0-12 Same as DATA			
A	Start	0		20	QS
B		1		21	PS
C		2		22	AT
D		13	QN	23	AN
E		14	PN	24	R
A'		15	QD	25	N
B'		16	GD, ASM	26	WCD, N(temp)
C'		17	Fric Const Rtn	27	PD
D'		18	Fric Const Pwr	28	M, Numerator N
E'		19	(1-WC)	29	PT

LABELS (Op 08)

INV ___	lnx ___	CE ___	CLR ___	x⇄t ___	x^2 ___
√x ___	1/x ___	STO ___	RCL ___	SUM ___	y^x ___
EE ___	(___	) ___	÷ ___	GTO ___	X ___
SBR ___	− ___	RST ___	+ ___	R/S ___	• ___
+/− ___	= ___	CLR ___	INV ___	log ___	CP ___
[illegible] ___	[illegible] ___	P→R ___	[illegible] ___	[illegible] ___	CMs ___
[illegible] ___	[illegible] ___	|x| ___	[illegible] ___	[illegible] ___	[illegible] ___
[illegible] ___	[illegible] ___	[illegible] ___	[illegible] ___	[illegible] ___	[illegible] ___
[illegible] ___	[illegible] ___	Σ+ ___	x̄ ___	[illegible] ___	[illegible] ___
[illegible] ___	DMS ___	π ___	[illegible] ___	[illegible] ___	[illegible] ___
[illegible] ___	[illegible] ___				

FLAGS	0	1	2	3	4	5	6	7	8	9
		X								

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FIGURE 12

APPENDIX 1 TI-59 PROGRAM LISTING (PART. 719.29)

This listing is an improved version of the program used for the examples in the text.

DATA

```
000  76 LBL
001  11  A
002  69 OP
003  00  00
004  01  1
005  06  6
006  01  1
007  03  3
008  03  3
009  07  7
010  01  1
011  03  3
012  69 OP
013  01  01
014  69 OP
015  05  05
016  98 ADV
017  01  1
018  06  6
019  01  1
020  07  7
021  03  3
022  03  3
023  03  3
024  07  7
025  02  2
026  03  3
027  69 OP
028  01  01
029  69 OP
030  05  05
031  43 RCL
032  01  01
033  91 R/S
034  99 PRT
035  42 STO
036  01  01
037  03  3
038  07  7
039  01  1
040  04  4
041  02  2
042  02  2
043  00  0
044  00  0
045  02  2
046  07  7
047  69 OP
048  01  01
049  01  1
050  07  7
051  03  3
052  01  1
053  02  2
054  02  2
055  03  3
056  07  7
057  02  2
058  03  3
059  69 OP
060  02  02
061  69 OP
062  05  05
063  43 RCL
064  02  02
065  91 R/S
066  99 PRT
067  42 STO
068  02  02
069  03  3
070  07  7
071  01  1
072  04  4
073  02  2
074  02  2
075  00  0
076  00  0
077  02  2
078  04  4
079  69 OP
080  01  01
081  01  1
082  06  6
083  00  0
084  00  0
085  00  0
086  00  0
087  00  0
088  00  0
089  00  0
090  00  0
091  69 OP
092  02  02
093  69 OP
094  05  05
095  43 RCL
096  03  03
097  91 R/S
098  99 PRT
099  42 STO
100  03  03
101  03  3
102  07  7
103  01  1
104  04  4
105  02  2
106  02  2
107  00  0
108  00  0
109  00  0
110  01  1
111  69 OP
112  01  01
113  01  1
114  06  6
115  00  0
116  00  0
117  00  0
118  00  0
119  00  0
120  00  0
121  00  0
122  00  0
123  69 OP
124  02  02
125  69 OP
126  05  05
127  43 RCL
128  04  04
129  91 R/S
130  99 PRT
131  42 STO
132  04  04
133  03  3
134  05  5
135  01  1
136  07  7
137  03  3
138  07  7
139  04  4
140  01  1
141  03  3
142  05  5
143  69 OP
144  01  01
145  03  3
146  01  1
147  00  0
148  00  0
149  02  2
150  04  4
151  01  1
152  06  6
153  00  0
154  00  0
155  69 OP
156  02  02
157  69 OP
158  05  05
159  43 RCL
160  05  05
161  91 R/S
162  99 PRT
163  42 STO
164  05  05
165  04  4
166  03  3
167  01  1
168  07  7
169  02  2
170  07  7
171  02  2
172  07  7
173  00  0
174  00  0
175  69 OP
176  01  01
177  02  2
178  03  3
179  01  1
180  07  7
181  01  1
182  03  3
183  01  1
184  06  6
185  00  0
186  00  0
187  69 OP
188  02  02
189  03  3
190  03  3
191  03  3
192  05  5
193  01  1
194  07  7
195  03  3
196  06  6
197  03  3
198  06  6
199  69 OP
200  03  03
201  69 OP
202  05  05
203  43 RCL
204  06  06
205  91 R/S
206  99 PRT
207  42 STO
208  06  06
209  69 OP
210  00  00
211  03  3
212  03  3
213  04  4
214  03  3
215  03  3
216  05  5
217  00  0
218  00  0
219  02  2
220  02  2
221  69 OP
222  01  01
223  03  3
224  05  5
225  01  1
226  03  3
227  01  1
228  06  6
229  00  0
230  00  0
231  00  0
232  00  0
233  69 OP
234  02  02
235  69 OP
236  05  05
237  43 RCL
238  07  07
239  91 R/S
240  99 PRT
241  42 STO
242  07  07
243  03  3
244  03  3
245  03  3
246  05  5
247  03  3
248  02  2
249  01  1
250  06  6
251  00  0
252  00  0
253  69 OP
254  01  01
255  00  0
256  01  1
257  02  2
258  04  4
259  02  2
260  07  7
261  00  0
262  00  0
263  02  2
264  02  2
265  69 OP
266  02  02
267  03  3
268  05  5
269  01  1
270  03  3
271  01  1
272  06  6
273  00  0
274  00  0
275  00  0
276  00  0
277  69 OP
278  03  03
279  69 OP
280  05  05
281  43 RCL
282  08  08
283  91 R/S
284  99 PRT
285  42 STO
286  08  08
287  69 OP
288  00  00
289  04  4
290  03  3
291  01  1
292  03  3
293  03  3
294  07  7
295  01  1
296  07  7
297  03  3
298  05  5
299  69 OP
300  01  01
301  02  2
302  02  2
303  03  3
304  05  5
305  01  1
306  03  3
307  01  1
308  06  6
309  69 OP
310  02  02
311  69 OP
312  05  05
313  43 RCL
314  09  09
315  91 R/S
316  99 PRT
317  42 STO
318  09  09
319  00  0
320  01  1
321  02  2
322  04  4
323  02  2
324  07  7
325  00  0
326  00  0
327  04  4
328  02  2
329  69 OP
330  01  01
331  02  2
332  04  4
333  03  3
334  06  6
335  01  1
336  05  5
337  00  0
338  00  0
339  00  0
340  00  0
341  69 OP
342  02  02
343  69 OP
344  05  05
345  43 RCL
346  10  10
347  91 R/S
348  99 PRT
349  42 STO
350  10  10
351  69 OP
352  00  00
353  02  2
354  02  2
355  00  0
356  01  1
357  03  3
358  05  5
359  00  0
360  00  0
361  00  0
362  00  0
363  69 OP
364  01  01
365  69 OP
366  05  05
367  43 RCL
368  11  11
369  91 R/S
370  99 PRT
371  42 STO
372  11  11
373  04  4
374  03  3
375  01  1
376  03  3
377  03  3
378  07  7
379  01  1
380  07  7
381  03  3
382  05  5
383  69 OP
384  01  01
385  01  1
386  05  5
387  04  4
388  01  1
389  03  3
390  07  7
391  00  0
392  00  0
393  69 OP
394  02  02
395  69 OP
396  05  05
397  43 RCL
398  12  12
399  91 R/S
400  99 PRT
401  42 STO
402  12  12
403  43 RCL
404  03  03
405  42 STO
406  13  13
407  42 STO
408  15  15
409  33 X²
410  42 STO
411  16  16
412  71 SBR
413  15  E
414  93  .
415  04  4
416  03  3
417  03  3
418  32 X:T
419  43 RCL
420  07  07
421  22 INV
422  77 GE
423  14  D
424  25 CLR
425  53  (
426  93  .
427  05  5
```

FIGURE 13

APPENDIX 1 TI-59 PROGRAM LISTING (PART. 719.29)

This listing is an improved version of the program used for the examples in the text.

```
428  05  5
429  55  ÷
430  43  RCL
431  07  07
432  54  )
433  45  Yx
434  93  .
435  02  2
436  01  1
437  65  ×
438  43  RCL
439  07  07
440  65  ×
441  43  RCL
442  17  17
443  95  =
444  42  STO
445  18  18
446  61  GTO
447  13  C
448  76  LBL
449  14  D
450  25  CLR
451  53  (
452  43  RCL
453  10  10
454  55  ÷
455  43  RCL
456  08  08
457  54  )
458  45  Yx
459  93  .
460  02  2
461  01  1
462  65  ×
463  43  RCL
464  08  08
465  65  ×
466  43  RCL
467  17  17
468  95  =
469  42  STO
470  18  18
471  76  LBL
472  13  C
473  43  RCL
474  05  05
475  42  STO
476  13  13
477  43  RCL
478  04  04
479  42  STO
480  14  14
481  43  RCL
482  13  13
483  75  -
484  43  RCL
485  14  14
486  95  =
487  42  STO
488  15  15
489  43  RCL
490  13  13
491  33  X²
492  75  -
493  43  RCL
494  14  14
495  33  X²
496  95  =
497  42  STO
498  16  16
499  71  SBR
500  15  E
```

```
501  01  1
502  75  -
503  43  RCL
504  12  12
505  95  =
506  42  STO
507  19  19
508  65  ×
509  43  RCL
510  08  08
511  85  +
512  43  RCL
513  12  12
514  65  ×
515  43  RCL
516  09  09
517  95  =
518  42  STO
519  00  00
520  69  OP
521  00  00
522  93  .
523  02  2
524  42  STO
525  25  25
526  25  CLR
527  91  R/S
528  76  LBL
529  15  E
530  53  (
531  53  (
532  43  RCL
533  16  16
534  55  ÷
535  43  RCL
536  15  15
537  54  )
538  45  Yx
539  93  .
540  02  2
541  01  1
542  55  ÷
543  53  (
544  43  RCL
545  13  13
546  55  ÷
547  43  RCL
548  15  15
549  54  )
550  45  Yx
551  93  .
552  01  1
553  55  ÷
554  43  RCL
555  16  16
556  33  X²
557  55  ÷
558  43  RCL
559  15  15
560  65  ×
561  43  RCL
562  02  02
563  65  ×
564  02  2
565  00  0
566  02  2
567  52  EE
568  94  +/-
569  08  8
570  54  )
571  42  STO
572  17  17
573  92  RTN
```

JET

```
000  76  LBL
001  11  A
002  02  2
003  05  5
004  01  1
005  07  7
006  03  3
007  07  7
008  69  OP
009  01  01
010  69  OP
011  05  05
012  69  OP
013  00  00
014  03  3
015  04  4
016  03  3
017  06  6
018  69  OP
019  01  01
020  69  OP
021  05  05
022  43  RCL
023  20  20
024  91  R/S
025  99  PRT
026  42  STO
027  20  20
028  03  3
029  03  3
030  03  3
031  06  6
032  69  OP
033  01  01
034  69  OP
035  05  05
036  43  RCL
037  21  21
038  91  R/S
039  99  PRT
040  42  STO
041  21  21
042  71  SBR
043  89  π
044  01  1
045  03  3
046  03  3
047  06  6
048  03  3
049  00  0
050  69  OP
051  01  01
052  69  OP
053  05  05
054  43  RCL
055  16  16
056  99  PRT
057  01  1
058  03  3
059  03  3
060  01  1
061  69  OP
062  01  01
```

```
063  69  OP
064  05  05
065  43  RCL
066  23  23
067  91  R/S
068  99  PRT
069  42  STO
070  23  23
071  01  1
072  03  3
073  03  3
074  07  7
075  69  OP
076  01  01
077  69  OP
078  05  05
079  43  RCL
080  22  22
081  91  R/S
082  99  PRT
083  42  STO
084  22  22
085  02  2
086  01  1
087  02  2
088  07  7
089  01  1
090  03  3
091  02  2
092  02  2
093  07  7
094  01  1
095  69  OP
096  01  01
097  69  OP
098  05  05
099  69  OP
100  00  00
101  91  R/S
102  43  RCL
103  23  23
104  55  ÷
105  43  RCL
106  22  22
107  95  =
108  42  STO
109  24  24
110  03  3
111  03  3
112  03  3
113  07  7
114  69  OP
115  01  01
116  69  OP
117  05  05
118  43  RCL
119  29  29
120  91  R/S
121  99  PRT
122  42  STO
123  29  29
124  76  LBL
125  23  LNX
126  85  +
127  43  RCL
128  07  07
129  65  ×
130  43  RCL
131  01  01
132  75  -
133  43  RCL
134  18  18
135  65  ×
```

```
136  53  (
137  43  RCL
138  13  13
139  45  Yx
140  01  1
141  93  .
142  07  7
143  09  9
144  54  )
145  95  =
146  76  LBL
147  34  ΓX
148  53  (
149  53  (
150  42  STO
151  14  14
152  75  -
153  43  RCL
154  21  21
155  54  )
156  55  ÷
157  43  RCL
158  07  07
159  54  )
160  34  ΓX
161  54  )
162  65  ×
163  43  RCL
164  23  23
165  65  ×
166  08  8
167  03  3
168  02  2
169  95  =
170  42  STO
171  13  13
172  85  +
173  43  RCL
174  20  20
175  95  =
176  42  STO
177  15  15
178  35  1/X
179  65  ×
180  53  (
181  43  RCL
182  00  00
183  65  ×
184  43  RCL
185  20  20
186  85  +
187  43  RCL
188  07  07
189  65  ×
190  43  RCL
191  13  13
192  54  )
193  95  =
194  42  STO
195  16  16
196  43  RCL
197  20  20
198  65  ×
199  43  RCL
200  12  12
201  55  ÷
202  43  RCL
203  15  15
204  95  =
205  42  STO
206  26  26
207  93  .
208  04  4
```

```
209  03  3
210  32  X:T
211  43  RCL
212  07  07
213  22  INV
214  77  GE
215  13  C
216  43  RCL
217  13  13
218  55  ÷
219  43  RCL
220  15  15
221  95  =
222  44  SUM
223  26  26
224  76  LBL
225  13  C
226  43  RCL
227  19  19
228  65  ×
229  43  RCL
230  20  20
231  65  ×
232  43  RCL
233  11  11
234  55  ÷
235  43  RCL
236  15  15
237  95  =
238  32  X:T
239  01  1
240  00  0
241  77  GE
242  14  D
243  02  2
244  02  2
245  02  2
246  07  7
247  03  3
248  05  5
249  69  OP
250  01  01
251  32  X:T
252  69  OP
253  05  05
254  99  PRT
255  04  4
256  03  3
257  01  1
258  05  5
259  69  OP
260  01  01
261  69  OP
262  05  05
263  43  RCL
264  26  26
265  99  PRT
266  02  2
267  02  2
268  01  1
269  06  6
270  69  OP
271  01  01
272  69  OP
273  05  05
274  43  RCL
275  16  16
276  99  PRT
277  03  3
278  04  4
279  01  1
280  06  6
281  69  OP
```

FIGURE 14

APPENDIX 1 TI-59 PROGRAM LISTING (PART. 719.29)

This listing is an improved version of the program used for the examples in the text.

```
282  01   01
283  69  OP
284  05   05
285  43  RCL
286  15   15
287  99  PRT
288  03   3
289  03   3
290  01   1
291  06   6
292  07   7
293  01   1
294  69  OP
295  01   01
296  69  OP
297  05   05
298  69  OP
299  00   00
300  43  RCL
301  27   27
302  91  R/S
303  99  PRT
304  42  STO
305  27   27
306  61  GTO
307  15   E
308  76  LBL
309  14   D
310  43  RCL
311  26   26
312  65   ×
313  93   .
314  05   5
315  05   5
316  85   +
317  53   (
318  01   1
319  75   -
320  43  RCL
321  26   26
322  54   )
323  65   ×
324  43  RCL
325  10   10
326  55   ÷
327  43  RCL
328  16   16
329  95   =
330  45  Yˣ
331  93   .
332  02   2
333  01   1
334  65   ×
335  43  RCL
336  16   16
337  65   ×
338  53   (
339  43  RCL
340  15   15
341  45  Yˣ
342  01   1
343  93   .
344  07   7
345  09   9
346  54   )
347  65   ×
348  43  RCL
349  17   17
350  95   =
351  85   +
352  43  RCL
353  06   06
354  85   +
355  53   (
356  43  RCL
357  16   16
358  65   ×
359  43  RCL
360  01   01
361  54   )
362  95   =
363  42  STO
364  27   27
365  76  LBL
366  15   E
367  43  RCL
368  20   20
369  65   ×
370  43  RCL
371  00   00
372  55   ÷
373  43  RCL
374  13   13
375  55   ÷
376  43  RCL
377  07   07
378  65   ×
379  53   (
380  53   (
381  53   (
382  43  RCL
383  11   11
384  55   ÷
385  43  RCL
386  21   21
387  54   )
388  45  Yˣ
389  01   1
390  93   .
391  02   2
392  65   ×
393  02   2
394  93   .
395  08   8
396  85   +
397  01   1
398  54   )
399  65   ×
400  43  RCL
401  19   19
402  85   +
403  43  RCL
404  12   12
405  54   )
406  95   =
407  42  STO
408  28   28
409  25  CLR
410  43  RCL
411  24   24
412  65   ×
413  02   2
414  95   =
415  85   +
416  53   (
417  53   (
418  01   1
419  75   -
420  43  RCL
421  24   24
422  65   ×
423  02   2
424  54   )
425  65   ×
426  53   (
427  43  RCL
428  28   28
429  33  X²
430  65   ×
431  43  RCL
432  24   24
433  33  X²
434  54   )
435  55   ÷
436  53   (
437  01   1
438  75   -
439  43  RCL
440  24   24
441  54   )
442  33  X²
443  54   )
444  95   =
445  75   -
446  53   (
447  01   1
448  93   .
449  02   2
450  65   ×
451  43  RCL
452  24   24
453  33  X²
454  65   ×
455  53   (
456  01   1
457  85   +
458  43  RCL
459  28   28
460  54   )
461  33  X²
462  54   )
463  95   =
464  42  STO
465  28   28
466  55   ÷
467  53   (
468  01   1
469  93   .
470  00   0
471  03   3
472  75   -
473  43  RCL
474  28   28
475  54   )
476  95   =
477  42  STO
478  26   26
479  75   -
480  43  RCL
481  25   25
482  95   =
483  55   ÷
484  43  RCL
485  25   25
486  95   =
487  50  I×I
488  32  X:T
489  93   .
490  00   0
491  00   0
492  05   5
493  77   GE
494  24  CE
495  43  RCL
496  26   26
497  85   +
498  43  RCL
499  25   25
500  95   =
501  55   ÷
502  02   2
503  95   =
504  42  STO
505  25   25
506  87  IFF
507  01   01
508  44  SUM
509  25  CLR
510  43  RCL
511  27   27
512  75   -
513  53   (
514  43  RCL
515  25   25
516  65   ×
517  53   (
518  43  RCL
519  14   14
520  75   -
521  43  RCL
522  27   27
523  54   )
524  54   )
525  95   =
526  42  STO
527  21   21
528  43  RCL
529  29   29
530  61  GTO
531  23  LNX
532  76  LBL
533  44  SUM
534  53   (
535  43  RCL
536  27   27
537  75   -
538  43  RCL
539  21   21
540  54   )
541  55   ÷
542  43  RCL
543  25   25
544  85   +
545  43  RCL
546  27   27
547  95   =
548  61  GTO
549  34  √X
550  76  LBL
551  24  CE
552  22  INV
553  87  IFF
554  01   01
555  33  X²
556  43  RCL
557  14   14
558  75   -
559  53   (
560  43  RCL
561  07   07
562  65   ×
563  43  RCL
564  01   01
565  54   )
566  85   +
567  53   (
568  43  RCL
569  18   18
570  65   ×
571  53   (
572  43  RCL
573  13   13
574  54   )
575  45  Yˣ
576  01   1
577  93   .
578  07   7
579  09   9
580  54   )
581  95   =
582  42  STO
583  29   29
584  76  LBL
585  33  X²
586  03   3
587  03   3
588  03   3
589  07   7
590  69  OP
591  01   01
592  69  OP
593  05   05
594  43  RCL
595  29   29
596  99  PRT
597  03   3
598  04   4
599  03   3
600  01   1
601  69  OP
602  01   01
603  43  RCL
604  13   13
605  69  OP
606  05   05
607  99  PRT
608  02   2
609  03   3
610  03   3
611  03   3
612  69  OP
613  01   01
614  69  OP
615  05   05
616  43  RCL
617  13   13
618  65   ×
619  43  RCL
620  29   29
621  55   ÷
622  05   5
623  02   2
624  09   9
625  01   1
626  00   0
627  95   =
628  99  PRT
629  03   3
630  04   4
631  03   3
632  06   6
633  01   1
634  05   5
635  69  OP
636  01   01
637  69  OP
638  05   05
639  71  SBR
640  89   π
641  43  RCL
642  22   22
643  75   -
644  43  RCL
645  23   23
646  95   =
647  55   ÷
648  43  RCL
649  16   16
650  65   ×
651  43  RCL
652  20   20
653  95   =
654  99  PRT
655  03   3
656  04   4
657  03   3
658  06   6
659  69  OP
660  01   01
661  43  RCL
662  20   20
663  69  OP
664  05   05
665  99  PRT
666  03   3
667  03   3
668  03   3
669  06   6
670  69  OP
671  01   01
672  43  RCL
673  21   21
674  69  OP
675  05   05
676  99  PRT
677  91  R/S
678  76  LBL
679  89   π
680  53   (
681  53   (
682  43  RCL
683  21   21
684  55   ÷
685  43  RCL
686  00   00
687  54   )
688  34  √X
689  35  1/X
690  55   ÷
691  06   6
692  09   9
693  01   1
694  85   +
695  53   (
696  43  RCL
697  19   19
698  65   ×
699  43  RCL
700  11   11
701  55   ÷
702  02   2
703  04   4
704  06   6
705  05   5
706  00   0
707  55   ÷
708  43  RCL
709  21   21
710  54   )
711  54   )
712  65   ×
713  43  RCL
714  20   20
715  95   =
716  42  STO
717  16   16
718  92  RTN
719  00   0
```

FIGURE 15

Appendix 2 HP-41C	INSTRUCTIONS FOR "JET"			SIZE: 030
Step	Instructions	Input	Function	Display
1	Set status and key in in the program			
2	Start program		XEQ "JET"	Data
3	Start Data Entry		R/S	
4	Enter or Accept	Depth	R/S	Depth=___
5	Enter or Accept	Tbg-Length	R/S	TBG Length=___
6	Enter or Accept	Tbg-I.D.	R/S	TBG ID=___
7	Enter or Accept	Tbg-O.D.	R/S	TBG OD=___
8	Enter or Accept	Return I.D.	R/S	Return ID=___
9	Enter or Accept	Well Head Press	R/S	Well Head Press=___
10	Enter or Accept	Pwr Grad.	R/S	PWR Grad=___
11	Enter or Accept	Prod. Oil Grad.	R/S	Oil Grad=___
12	Enter or Accept	Water Grad.	R/S	Water Grad=___
13	Enter or Accept	Oil Visc.	R/S	Oil Visc=___
14	Enter or Accept	Gas Oil Ratio	R/S	GOR=___
15	Enter or Accept	Water Cut	R/S	Water Cut=___
16	Calculates GS, Friction Constants and (1-WC)			Jet
17	Start Jet Calculation		R/S	
18	Enter or Accept	Prod. Rate	R/S	QS=___
19	Enter or Accept	Suct. Press	R/S	PS=___
20	Calculates minimum suction area		R/S	ASM=___
21	Enter or Accept	Nozzle Area	R/S	AN=___
22	Enter or Accept	Throat Area	R/S	AT=___
23	Set flag 01 for operating pressure required at given PS and QS. Do not set Flag 01 for constant operating pressure.	SF01		
24	Enter or Accept	Operating Pressure	R/S	PT=___
25	It GLR in Return $\geqslant 10$, Display GLR, WC, GD, QD			GLR=___,WC=___, GD=___,QD=___,
	Enter PD		R/S	PD=?
26	Displays solution, Operating Press., Nozzle Flow, Horsepower, Cavitation Limit, Prod. Rate, Pump Suction Pressure			PT=___, QN=___, HP=___, QSC=___, QS=___, PS=___
27	New Point		R/S	Jet(Step 17)
28	New Data		EXQ"JET"	Data(Step 2)

STORAGE

R00	GS	R10	Visc. Oil(μo)	R20	QS
R01	Depth(D)	R11	Gas Oil Ratio(GOR)	R21	PS
R02	Tbg. Length(L)	R12	Water Cut(WC)	R22	AT
R03	Tbg. I.D.	R13	D1, QN	R23	AN
R04	Tbg. O.D.	R14	D2, PN	R24	R
R05	Rtn. I.D.	R15	(D1-D2), QD	R25	N
R06	Flowline Press(PWH)	R16	$(D1^2-D2^2)$, GD, ASM	R26	WCD,N(temp)
R07	Grad.Pwr(GN)	R17	Fric. Const. Rtn.	R27	PD
R08	Grad. Oil(GD)	R18	Fric. Const. Pwr.	R28	M,Numer. N
R09	Grad Water(GW)	R19	(1-WC)	R29	PT

FIGURE 16

APPENDIX 2
HP-41C PROGRAM LISTING (SIZE 030)

This listing is an improved version of the program used for the examples in the text.

```
01♦LBL "JET"
02 "DATA"
03 AVIEW
04 STOP
05 FIX 0
06 RCL 01
07 "DEPTH="
08 ARCL X
09 AVIEW
10 STOP
11 STO 01
12 RCL 02
13 "TBG LENGTH="
14 ARCL X
15 AVIEW
16 STOP
17 STO 02
18 FIX 3
19 RCL 03
20 "TBG ID="
21 ARCL X
22 AVIEW
23 STOP
24 STO 03
25 RCL 04
26 "TBG OD="
27 ARCL X
28 AVIEW
29 STOP
30 STO 04
31 RCL 05
32 "RETURN ID="
33 ARCL X
34 AVIEW
35 STOP
36 STO 05
37 FIX 0
38 RCL 06
39 "WELL HEAD PRES="
40 ARCL X
41 AVIEW
42 STOP
43 STO 06
44 FIX 3
45 RCL 07
46 "PWR GRAD="
47 ARCL X
48 AVIEW
49 STOP
50 STO 07
51 RCL 08
52 "PROD OIL GRAD="
53 ARCL X
54 AVIEW
55 STOP
56 STO 08
57 RCL 09
58 "WATER GRAD="
59 ARCL X
60 AVIEW
61 STOP
62 STO 09
63 FIX 2
64 RCL 10
65 "OIL VISC="
66 ARCL X
67 AVIEW
68 STOP
69 STO 10
70 RCL 11
71 "GOR="
72 ARCL X
73 AVIEW
74 STOP
75 STO 11
76 FIX 2
77 RCL 12
78 "WATER CUT="
79 ARCL X
80 AVIEW
81 STOP
82 STO 12
83 RCL 03
84 STO 13
85 STO 15
86 ENTER↑
87 *
88 STO 16
89 XEQ E
90 .433
91 RCL 07
92 X<=Y?
93 GTO D
94 ENTER↑
95 .55
96 X<>Y
97 /
98 .21
99 Y↑X
100 *
101 RCL 17
102 *
103 STO 18
104 GTO C
105♦LBL D
106 RCL 10
107 RCL 08
108 /
109 .21
110 Y↑X
111 RCL 08
112 *
113 RCL 17
114 *
115 STO 18
116♦LBL C
117 RCL 05
118 STO 13
119 RCL 04
120 STO 14
121 -
122 STO 15
123 RCL 13
124 ENTER↑
125 *
126 RCL 14
127 ENTER↑
128 *
129 -
130 STO 16
131 XEQ E
132 1
133 RCL 12
134 -
135 STO 19
136 RCL 08
137 *
138 RCL 09
139 RCL 12
140 *
141 +
142 STO 00
143 .2
144 STO 25
145 GTO B
146♦LBL E
147 RCL 16
148 RCL 15
149 /
150 .21
151 Y↑X
152 RCL 13
153 RCL 15
154 /
155 .1
156 Y↑X
157 /
158 RCL 16
159 ENTER↑
160 *
161 /
162 RCL 15
163 /
164 RCL 02
165 *
166 202 E-8
167 *
168 STO 17
169 RTN
170♦LBL B
171 "JET"
172 AVIEW
173 STOP
174 FIX 0
175 RCL 20
176 "QS="
177 ARCL X
178 AVIEW
179 STOP
180 STO 20
181 RCL 21
182 "PS="
183 ARCL X
184 AVIEW
185 STOP
186 STO 21
187 FIX 4
188 XEQ a
189 "ASM="
190 ARCL X
191 AVIEW
192 STOP
193 RCL 23
194 "AN="
195 ARCL X
196 AVIEW
197 STOP
198 STO 23
199 RCL 22
200 "AT="
201 ARCL X
202 AVIEW
203 STOP
204 STO 22
205 "FLAG?"
206 AVIEW
207 STOP
208 /
209 STO 24
210 FIX 0
211 RCL 29
212 "PT="
213 ARCL X
214 AVIEW
215 STOP
216 STO 29
217♦LBL 01
218 RCL 07
219 RCL 01
220 *
221 +
222 RCL 13
223 1.79
224 Y↑X
225 RCL 18
226 *
227 -
228♦LBL 02
229 STO 14
230 RCL 21
231 -
232 RCL 07
233 /
234 SQRT
235 RCL 23
236 *
237 832
238 *
239 STO 13
240 RCL 20
241 +
242 STO 15
243 1/X
244 RCL 00
245 RCL 20
246 *
247 RCL 07
248 RCL 13
249 *
250 +
251 *
252 STO 16
253 RCL 20
254 RCL 12
255 *
```

FIGURE 17

APPENDIX 2
HP-41C PROGRAM LISTING (SIZE 030)

```
256 RCL 15
257 /
258 STO 26
259 .43
260 RCL 07
261 X<=Y?
262 GTO C
263 RCL 13
264 RCL 15
265 /
266 ST+ 26
267♦LBL C
268 RCL 19
269 RCL 20
270 *
271 RCL 11
272 *
273 RCL 15
274 /
275 10
276 X>Y?
277 GTO D
278 "GLR="
279 ARCL Y
280 AVIEW
281 PSE
282 PSE
283 FIX 2
284 RCL 26
285 "WC="
286 ARCL X
287 AVIEW
288 PSE
289 PSE
290 RCL 16
291 "GD="
292 ARCL X
293 AVIEW
294 PSE
295 PSE
296 FIX 0
297 RCL 15
298 "QD="
299 ARCL X
300 AVIEW
301 PSE
302 PSE
303 RCL 27
304 "PD=?"
305 ARCL X
306 AVIEW
```

```
307 STOP
308 STO 27
309 GTO E
310♦LBL D
311 RCL 26
312 .55
313 *
314 1
315 RCL 26
316 -
317 RCL 10
318 *
319 +
320 RCL 16
321 /
322 .21
323 Y↑X
324 RCL 16
325 *
326 RCL 15
327 1.79
328 Y↑X
329 *
330 RCL 17
331 *
332 RCL 06
333 +
334 RCL 16
335 RCL 01
336 *
337 +
338 STO 27
339♦LBL E
340 RCL 20
341 RCL 00
342 *
343 RCL 13
344 /
345 RCL 07
346 /
347 RCL 11
348 RCL 21
349 /
350 1.2
351 Y↑X
352 2.8
353 *
354 1
355 +
356 RCL 19
357 *
```

```
358 RCL 12
359 +
360 *
361 STO 28
362 RCL 24
363 2
364 *
365 ENTER↑
366 ENTER↑
367 1
368 X<>Y
369 -
370 RCL 28
371 RCL 24
372 *
373 X↑2
374 *
375 1
376 RCL 24
377 -
378 X↑2
379 /
380 +
381 1.2
382 RCL 24
383 X↑2
384 *
385 1
386 RCL 28
387 +
388 X↑2
389 *
390 -
391 ENTER↑
392 ENTER↑
393 1.03
394 X<>Y
395 -
396 /
397 STO 26
398 RCL 25
399 -
400 RCL 25
401 /
402 ABS
403 .005
404 X>Y?
405 GTO 04
406 RCL 26
407 RCL 25
408 +
```

```
409 2
410 /
411 STO 25
412 FS? 01
413 GTO 03
414 RCL 14
415 RCL 27
416 -
417 RCL 25
418 *
419 RCL 27
420 X<>Y
421 -
422 STO 21
423 RCL 29
424 GTO 01
425♦LBL 03
426 RCL 27
427 RCL 21
428 -
429 RCL 25
430 /
431 RCL 27
432 +
433 GTO 02
434♦LBL 04
435 FS? 01
436 GTO 05
437 GTO 06
438♦LBL 05
439 RCL 14
440 RCL 07
441 RCL 01
442 *
443 -
444 RCL 13
445 1.79
446 Y↑X
447 RCL 18
448 *
449 +
450 STO 29
451♦LBL 06
452 RCL 29
453 "PT="
454 ARCL X
455 AVIEW
456 STOP
457 RCL 13
458 "QN="
459 ARCL X
```

```
460 AVIEW
461 STOP
462 *
463 52910
464 /
465 "HP="
466 ARCL X
467 AVIEW
468 STOP
469 RCL 22
470 RCL 23
471 -
472 XEQ a
473 /
474 RCL 20
475 *
476 "QSC="
477 ARCL X
478 AVIEW
479 STOP
480 RCL 20
481 "QS="
482 ARCL X
483 AVIEW
484 STOP
485 RCL 21
486 "PS="
487 ARCL X
488 AVIEW
489 STOP
490 GTO B
491♦LBL a
492 RCL 00
493 RCL 21
494 /
495 SQRT
496 691
497 /
498 RCL 19
499 RCL 11
500 *
501 24650
502 /
503 RCL 21
504 /
505 +
506 RCL 20
507 *
508 STO 16
509 RTN
510 .END.
```

FIGURE 18

TABLE 1
NOZZLE AND THROAT SIZES

KOBE				NATIONAL				GUIBERSON			
Nozzle		Throat		Nozzle		Throat		Nozzle		Throat	
#	Area	#	Area	#	Area	#	Area	#	Area	#	Area
1	.0024	1	.0060	1	.0024	1	.0064	DD	.0016	000	.0044
2	.0031	2	.0077	2	.0031	2	.0081	CC	.0028	00	.0071
3	.0040	3	.0100	3	.0039	3	.0104	BB	.0038	0	.0104
4	.0052	4	.0129	4	.0050	4	.0131	A	.0055	1	.0143
5	.0067	5	.0167	5	.0064	5	.0167	B	.0095	2	.0189
6	.0086	6	.0215	6	.0081	6	.0212	C	.0123	3	.0241
7	.0111	7	.0278	7	.0103	7	.0271	D	.0177	4	.0314
8	.0144	8	.0359	8	.0131	8	.0346	E	.0241	5	.0380
9	.0186	9	.0464	9	.0167	9	.0441	F	.0314	6	.0452
10	.0240	10	.0599	10	.0212	10	.0562	G	.0452	7	.0531
11	.0310	11	.0774	11	.0271	11	.0715	H	.0661	8	.0661
12	.0400	12	.1000	12	.0346	12	.0910	I	.0855	9	.0804
13	.0517	13	.1292	13	.0441	13	.1159	J	.1257	10	.0962
14	.0668	14	.1668	14	.0562	14	.1476	K	.1590	11	.1195
15	.0863	15	.2154	15	.0715	15	.1879	L	.1963	12	.1452
16	.1114	16	.2783	16	.0910	16	.2392	M	.2463	13	.1772
17	.1439	17	.3594	17	.1159	17	.3046	N	.3117	14	.2165
18	.1858	18	.4642	18	.1476	18	.3878	P	.3848	15	.2606
19	.2400	19	.5995	19	.1879	19	.4938			16	.3127
20	.3100	20	.7743	20	.2392	20	.6287			17	.3750
		21	1.0000							18	.4513
		22	1.2916							19	.5424
		23	1.6681							20	.6518
		24	2.1544								

Nozzle	Throat	R	Nozzle	Throat	R	
N	N-1	.517 A-	N	N-1	.483 X	Guiberson Ratios Listed in Table 2
N	N	.400 A	N	N	.380 A	
N	N+1	.310 B	N	N+1	.299 B	
N	N+2	.240 C	N	N+2	.235 C	
N	N+3	.186 D	N	N+3	.184 D	
N	N+4	.144 E	N	N+4	.145 E	

TABLE 2 — GUIBERSON RATIOS AND THROAT ANNULUS AREAS (in²)

Nozzle									
DD	Throats	000	00						
	R	.36	.22						
	AS	.0028	.0056						
CC	Throats	000	00	0	1				
	R	.64	.40	.27	.20				
	AS	.0016	.0043	.0076	.0115				
BB	Throats	00	0	1	2				
	R	.54	.37	.27	.20				
	AS	.0032	.0065	.0105	.0150				
A	Throats	0	1	2	3				
	R	.53	.39	.29	.23				
	AS	.0048	.0088	.0133	.0185				
B	Throats	0	1	2	3	4	5	6	
	R	.92	.66	.50	.40	.30	.25	.21	
	AS	.0009	.0048	.0094	.0145	.0219	.0285	.0357	
C	Throats	1	2	3	4	5	6	7	
	R	.86	.65	.51	.39	.32	.27	.23	
	AS	.0020	.0066	.0118	.0191	.0257	.0330	.0408	
D	Throats	3	4	5	6	7	8	9	
	R	.74	.56	.46	.39	.33	.27	.22	
	AS	.0064	.0137	.0203	.0276	.0354	.0484	.0628	
E	Throats	4	5	6	7	8	9	10	11
	R	.77	.63	.53	.45	.36	.30	.25	.20
	AS	.0074	.0140	.0212	.0290	.0420	.0564	.0722	.0954
F	Throats	6	7	8	9	10	11	12	
	R	.69	.59	.48	.39	.33	.26	.22	
	AS	.0138	.0217	.0346	.0490	.0648	.0880	.1138	
G	Throats	8	9	10	11	12	13	14	
	R	.68	.56	.47	.38	.31	.26	.21	
	AS	.0208	.0352	.0510	.0742	.1000	.1320	.1712	
H	Throats	10	11	12	13	14	15	16	
	R	.69	.55	.45	.37	.30	.25	.21	
	AS	.0302	.0534	.0792	.1112	.1504	.1945	.2467	
I	Throats	11	12	13	14	15	16	17	
	R	.72	.59	.48	.40	.33	.27	.23	
	AS	.0339	.0597	.0917	.1309	.1750	.2272	.2895	
J	Throats	13	14	15	16	17	18	19	
	R	.71	.58	.48	.40	.34	.28	.23	
	AS	.0515	.0908	.1349	.1871	.2493	.3256	.4167	
K	Throats	15	16	17	18	19	20		
	R	.61	.51	.42	.35	.29	.24		
	AS	.1015	.1537	.2160	.2922	.3833	.4928		
L	Throats	16	17	18	19	20			
	R	.63	.52	.44	.36	.30			
	AS	.1164	.1787	.2549	.3460	.4555			
M	Throats	17	18	19	20				
	R	.66	.55	.45	.38				
	AS	.1287	.2050	.2961	.4055				
N	Throats	18	19	20					
	R	.69	.57	.48					
	AS	.1395	.2306	.3401					
P	Throats	19	20						
	R	.71	.59						
	AS	.1575	.2670						

TABLE 3 KOBE

NOZZLE	THROAT ANNULUS AREA (IN^2)					
	A-	A	B	C	D	E
1		.0036	.0053	.0076	.0105	.0143
2	.0029	.0046	.0069	.0098	.0136	.0184
3	.0037	.0060	.0089	.0127	.0175	.0231
4	.0048	.0077	.0115	.0164	.0227	.0308
5	.0062	.0100	.0149	.0211	.0293	.0397
6	.0080	.0129	.0192	.0273	.0378	.0513
7	.0104	.0167	.0248	.0353	.0488	.0663
8	.0134	.0216	.0320	.0456	.0631	.0856
9	.0174	.0278	.0414	.0589	.0814	.1106
10	.0224	.0360	.0534	.0760	.1051	.1428
11	.0289	.0464	.0690	.0981	.1358	.1840
12	.0374	.0599	.0891	.1268	.1749	.2382
13	.0483	.0774	.1151	.1633	.2265	.3076
14	.0624	.1001	.1482	.2115	.2926	.3974
15	.0806	.1287	.1920	.2731	.3780	.5133
16	.1036	.1668	.2479	.3528	.4881	.6629
17	.1344	.2155	.3203	.4557	.6304	.8562
18	.1735	.2784	.4137	.5885	.8142	1.1058
19	.2242	.3595	.5343	.7600	1.0516	1.4282
20	.2896	.4643	.6901	.9817	1.3583	1.8444

TABLE 4 — NATIONAL

NOZZLE	THROAT ANNULUS AREA (IN^2)					
	X	A	B	C	D	E
1		.0040	.0057	.0080	.0108	.0144
2	.0033	.0050	.0073	.0101	.0137	.0183
3	.0042	.0065	.0093	.0129	.0175	.0233
4	.0054	.0082	.0118	.0164	.0222	.0296
5	.0068	.0104	.0150	.0208	.0282	.0377
6	.0087	.0133	.0191	.0265	.0360	.0481
7	.0111	.0169	.0243	.0338	.0459	.0612
8	.0141	.0215	.0310	.0431	.0584	.0779
9	.0179	.0274	.0395	.0548	.0743	.0992
10	.0229	.0350	.0503	.0698	.0947	.1264
11	.0291	.0444	.0639	.0888	.1205	.1608
12	.0369	.0564	.0813	.1130	.1533	.2046
13	.0469	.0718	.1035	.1438	.1951	.2605
14	.0597	.0914	.1317	.1830	.2484	.3316
15	.0761	.1164	.1677	.2331	.3163	.4223
16	.0969	.1482	.2136	.2968	.4028	.5377
17	.1234	.1888	.2720	.3779	.5128	
18	.1571	.2403	.3463	.4812		
19	.2000	.3060	.4409			
20	.2546	.3896				

TABLE 5 — SAMPLE TI-59 TAPES

DATA ENTRY	JET WITH FLAG SET	JET WITHOUT FLAG 3000 psi	JET WITHOUT FLAG 3500 psi
DATA	JET	JET	JET
DEPTH	QS	QS	QS
5000.	500.	500.	500.
TBG LENGTH	PS	PS	PS
6000.	1000.	1000.	800.
TBG ID	ASM	ASM	ASM
1.995	0141220402	.0141220402	.0157889209
TBG OD	AN	AN	AN
2.375	0.0055	0.0055	0.0055
RETURN ID	AT	AT	AT
4.892	0.0241	0.0241	0.0241
WELL HEAD PRESS	FLAG?	FLAG?	FLAG?
100.	PT	PT	PT
PWR GRAD	3000.	3000.	3500.
0.353	PT	PT	PT
PROD OIL GRAD	3283.531495	3000.	3500.
0.353	QN	QN	QN
WATER GRAD	489.	462.	507.
0.446	HP	HP	HP
OIL VISC	30.40739505	26.24379796	33.56968078
2.5	QSC	QSC	QSC
GOR	658.5450736	702.9793516	627.1974491
0.	QS	QS	QS
WATER CUT	500.	500.	500.
0.3	PS	PS	PS
	1000.	1139.	907.

TABLE 6 — WELL DATA FOR NATIONAL WELL

Pump Depth	9706 ft	Oil Viscosity	7 cp
Tubing Length	9706 ft	Gas-Oil Ratio	1000 scf/BBL
Tubing I.D.	1.900 in	Water Cut	.19
Tubing O.D.	2.375 in	Bottom Hole Temp.	182 °F
Return I.D.	6.500 in	Well Head Temp	80 °F
Well Head Press.	120 psi	Static Bottom Hole Press	1800 psi
Power Fluid	30 ° API	Flowing Bottom Hole Press	1550 psi
Oil Gravity	30 ° API	Production Rate	195-205 BPD
Water Gravity	.455 psi/ft	Gas Gravity	.65

TABLE 7 — WELL DATA FOR GUIBERSON WELL

Pump Depth	6718 ft	Oil Viscosity	1.6 cp
Tubing Length	6718 ft	Gas-Oil Ratio	2500 scf/BBL
Tubing I.D.	1.995 in	Water Cut	.90
Tubing O.D.	2.375 in	Bottom Hole Temp	120° F
Return I.D.	4.05 in	Well Head Temp	80° F
Well Head Press.	100 psi	Static Bottom Hole Press.	2000 psi
Power Fluid	Water	Flowing Bottom Hole Press	1566 psi
Oil Gravity	52° API	Production Rate	700 BPD
Water Gradient	.455 psi/ft	Gas Gravity	.85