Application of Real-Time Measurement of Motor Power to Determination of Beam Pump Efficiency

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ABSTRACT

A systematic study was undertaken in order to establish a procedure by which the effect of operating conditions on the efficiency of beam pumping systems can be determined with a minimum of expense. The study concentrated on the effect of easily controllable parameters such as direction of rotation, counterbalance effect, motor selection, torque mode for variable torque motors, tubing back pressure, stuffing box friction and motor slip on the energy usage.

The paper describes the instrumentation, data acquisition and processing system which allows accurate measurement of instantaneous motor power during a pump stroke. This measurement was correlated with dynamometer measurements in order to determine the surface system efficiency. Calculation of the downhole pump dynamometer allows determination of the effect of operating conditions on the volumetric efficiency of the pump. From these measurements, an overall efficiency can be established as a means of comparison; that is , the overall work output at the pump versus the work input at the motor.

INTRODUCTION

The effort to reduce lifting costs in beam pumping operations has focused the attention of production personnel to reduction of electrical power consumption. A recent study[1] shows that properly operated beam pumping systems provide very good efficiencies in the order of 1.1 to 1.4 kW-hr/bbl when lifting fluid from 4300 to 6700 ft respectively. Equivalent submersible pumping systems exhibited efficiencies of the order of 1.8 to 2.5 kW-hr/bbl. Their study shows that when properly designed and operated, the beam pumping systems exhibit overall efficiencies of the order of 57%, where overall efficiency was defined as the ratio of the power out of the system (based on net depth of lift, fluid gravity and production rate) to the power into the system as measured kW-hr.

Unfortunately a large number of pumping systems are not properly designed nor properly operated to achieve such a high efficiency. One of the reasons stems from the fact that it is not customary to routinely take measurements of electrical power consumption of individual beam pumping units. The one electrical measurement that is commonly made in the oil field is motor current, using a standard clamp-on amp probe, with the objective of adjusting the unit's counterbalance. Normally current data is displayed at a rate of one reading per second and corresponds to the average of the apparent motor current over the last second. The majority of operators do not have readily available means of determining the true electrical power consumption of a given beam pump and thus cannot establish whether it is operating efficiently or the motor is oversized or even if the unit is properly balanced.

The system described in this paper provides an accurate means to determine the performance of a beam pumping system based on the measurement of instantaneous motor power using a set of power transducers in conjunction with the digital Well Analyzer system[2]. The Well Analyzer is a PC-based data acquisition and analysis package that allows automatic measurement of annular fluid level and accurate casing-head pressure, calculation of producing bottom hole pressure, measurement of polished rod dynamometer data and calculation of downhole pump dynamometer cards and includes the measurement of motor current and motor power.

PERFORMANCE OF ELECTRICALLY POWERED BEAM PUMPS

The cyclic nature of the pumping system and the variable loading which is dependent on the mechanics and efficiency of the down-hole pump and sucker rod string, result in a continuously variable current flow over a pumping cycle. This translates in the fact that averaged values of apparent current are not indicative of the actual power usage and requirements. Moreover to reduce torque requirements, counterbalancing of the rod load plus one half of the fluid load is commonly used and most installations exhibit torque reversals during the pumping cycle even if properly balanced. This means that during portions of a pump stroke the prime mover drives the gear box and that during other portions the gearbox drives the motor. In the first case the motor is using electrical power, in the second case it is generating electricity. The most common indication that this reversal in current flow is taking place is the widely observed "gearbox backlash". The clanking sound which may be noted in the gearbox at such times is due to the transfer of load from the front side to the back side of the gear teeth.

Motor Types

In electrified oil fields, most beam pumping units are powered by three-phase induction motors which exhibit performance characteristics similar to those shown in Figure 1. In this figure, three parameters are plotted as a function of the motor speed in RPM: the torque, the apparent or actual line current and the efficiency. The motor is rated at an operating point near the maximum efficiency and at such a current so as not to exceed the recommended operating temperature.[3,4,5,6,7]

The torque produced by the motor varies from a large quantity at zero RPM (locked rotor) and speeds below 1000 RPM then rapidly decreases to zero at the synchronous speed (1200 RPM).

Correspondingly the motor current is a maximum at zero speed and reduces to a minimum at the synchronous speed. This minimum current generally is of the order of 1/3 of the motor full load rated current and is defined as the magnetizing current which is used in providing the motor's rotating magnetic field plus thermal losses. At synchronous speed the motor current is lagging 90 degrees the voltage applied to the motor's stator windings. The motor's efficiency is defined as the ratio of output to input power. It ranges from zero at locked rotor conditions (power = torque * speed) then increases to a maximum near motor rated speed and decreases sharply to zero at the synchronous speed.

The diagrams also indicate that if the motor is driven past the synchronous speed into the regenerative region the current and efficiency curves are nearly mirror images of the motoring curves relative to the synchronous speed. The torque is also mirrored but with the opposite sign. This indicates that torque is required to drive the motor past the synchronous speed and that the motor is essentially acting as a brake. Applying these characteristics to the cyclical nature of the beam pumping system the following may be concluded:

- Since the polished rod load is cyclical so will be the torque on the reducer. The direct relationship between torque and motor current will thus result in a cyclical motor current.

- The motor's RPM will also exhibit a cyclical behavior varying below and above the motor rated speed if the motor is properly sized.

- If the reducer torque becomes zero during the pumping cycle the motor will tend to run at its synchronous speed. At this condition the motor current will be minimum.

- If the unit's counterbalance and inertia are sufficient to reverse the torque on the reducer, the motor will be driven into the regenerative mode. The current will increase in proportion to the speed in excess of synchronous speed. This power is returned to the distribution system.

Standard characteristics of motors include the power, current, speed, efficiency, torque and slip at various operating points. These quantities can be used to determine the performance of the motor under varying load conditions. The National Electric Manufacturers Association (NEMA) developed specifications and performance criteria for motors. Motors that are applied for beam pumping operations include: NEMA- D, NEMA-B, and ULTRA HIGH SLIP

NEMA- D motors are designed for high torque and high acceleration applications. Two types are available: normal slip (5-8%) and high slip (8-13%).

SLIP is defined as the ratio of the speed variation between fully loaded condition and zero load to the synchronous speed of the motor expressed as a percentage:

$$SLIP = 100 * \{\Omega sync - \Omega(t)\} / \Omega sync$$

where

$\Omega(t)$ = is the instantaneous speed of the shaft.

$\Omega sync$ = the synchronous speed of the motor.

As the torque increases the speed decreases and vice versa. The efficiency of the motor also tends to decrease as the slip increases.

NEMA - B motors are designed for relatively constant loads with nominal starting torque and slip characteristics less than 5%.

ULTRA HIGH SLIP motors are generally custom designs for beam pumping applications. Their principal characteristic is to provide slips as high as 50%, with the intent of providing high torque when needed during the pumping cycle. Each size motor exhibits multiple ratings depending on how the windings are connected. Generally four settings are possible (high, medium, medium-low and low torque). The minimum horsepower and lowest current occur for the low torque mode while the maximum horsepower and highest current occur for the high torque mode. Correspondingly the slip will be maximum in the low torque mode (35-45%) and minimum in the high torque mode (10-15%)

A computer modeling study of the performance of various motor types[6] showed the importance of properly selecting and sizing the motor to fit the particular pumping application. This study also concluded that the minimum operating cost and minimum capital investment can be achieved by selecting motors with less slip. Correspondingly as the motor slip is reduced there is an increase in the torque peak to be supported by the reducer. This and other studies[8,9,10,11] have demonstrated the importance of accurate measurements of motor power as a means to determine the most efficient operating conditions of beam pumping systems.

POWER MEASUREMENT

The average operator has not had the capability to easily determine power utilization of a beam pump system. Most installations are such that multiple units are connected to a single electrical meter. In these instances it would be necessary to turn off all units, except the one being tested, in order to measure the power usage of an individual unit (or install a temporary single meter). This is generally not possible due to the loss of production. For those instances where each well is metered individually, the integrating power meter can be used to measure the use of electricity. Care must be exercised to identify the correct meter factor and whether the meter is free or is ratcheted (does not account for power generation). These meters however do not give an indication of the variation of power utilization during the pumping cycle. Thus they are not useful in determining peak values which would indicate overbalanced (or underbalanced conditions).

Current Measurement and Analysis

The most common electrical performance measurement related to beam pumping is determination of the maximum motor current during the upstroke and downstroke of a pumping cycle, with the purpose of determining whether the unit is properly balanced. These measurements are undertaken by clamping a current meter onto one of the three conductors feeding power to the motor. Depending on the meter (digital or analog) the indicated values give an indication of a smoothed current function but not necessarily the peak values. Also these meters are not able to differentiate between power being supplied to the motor and power generated by overdriving the motor with the counterbalance.

High rate digitization of the instantaneous current and digital processing of the signal[12] allows calculation of the instantaneous power factor and determination of the active current. This in turn allows estimating (within 10-15%) the power utilization per pump cycle. Field measurements have shown however that in the majority of the wells tested, the results varied significantly when measurements were made on each of the three phases. This is an indication that due to electrical imbalance of the phases an accurate measurement of power requires simultaneous measurement of the current flow in at least two phases and voltage measurement of all three conductors. However the thermal current loading can be calculated to determine motor overloading or under loading

Instantaneous Power Measurement

A system was designed and implemented to undertake quantitative measurement of instantaneous power using sensors consisting of two current probes and three voltage leads, which are connected to the three phase leads inside the units switch box.

Special purpose integrated circuits process the sensors data so as to generate an analog signal which is proportional to the instantaneous power. The sensors are calibrated so as to determine the power with an accuracy better than 5% provided the probes are correctly installed. The measurement procedure must be followed closely in order to obtain data of good and repeatable quality. In general the user is interested in establishing the power use of the pumping system when it is operating under steady state conditions. In the case that the well is pumping a full barrel and then begins to pump a partial barrel of liquid, the measured power will vary and will not be representative of the normal operating conditions. Therefore it is advisable to insure that the well being tested is produced while testing at the same conditions as normal operations. This can easily be undertaken by running quick dynamometer measurements. When power measurements are to be made with the purpose of comparing the efficiency of different motor wiring options (low, medium or high torque for example) it is important not to move the current sensors after installation so as not to change the relative position of the wire within the current sensor. Such change would cause small variations in the readings which might invalidate the conclusions of the test. The data for two successive pump cycles are acquired with a high speed, high precision A/D converter and processed by a portable PC. The software then generates graphic and tabular output screens which are saved on disk for subsequent printing.
Figure 2 presents the information related to energy utilization. Displayed at the left as a function of time are the apparent current and the instantaneous power, over one complete stroke of the pumping unit. Note that at the top of the graph is indicated the position of the polished rod. Time increases from left to right. Thus the first half of the plot corresponds to the up-stroke and the second half to the down-stroke. The horizontal dashed line corresponds to zero power and current. Values below this line indicate electrical generation.

On the right side of the figure are summarized the principal efficiency parameters. The first two lines indicate the energy cost per month assuming continuous operation (24 hours per day and 30 days per month) based on the cost per KWH input by the user.

The operating cost is also calculated on the basis of a barrel of fluid pumped and a stock tank barrel of oil produced. These values are calculated from the production rates which were entered in the well data file and based on the most recent well test. It should be noted that often well test data is not as accurate as one may desire. Dynamometer measurements were undertaken simultaneously with the power measurement to determine the downhole pump displacement. This displacement should be reasonably close to the volume reported from the well test. If this is not true, then the well production may have changed significantly or the well test was not reported accurately. In general the pump displacement from the downhole dynamometer when properly measured is likely to be more accurate than the well test.

Motor Performance

The performance of an induction motor subjected to the cyclical loading of a beam pumping system is described by values averaged over one pump stroke.

- **RMS** current is defined as the square root of the average of the squared currents over a pumping cycle. This quantity is also referred to as the **thermal current** since it determines the heating losses in the motor. A motor is a current-rated device and the RMS current should not excessively exceed the nameplate full-load current rating. Motor loading is reflected by the ratio of the RMS current to the nameplate current rating. A ratio of 60% or less is an indication that the motor might be oversized.

- **CLF** Cyclic Load Factor is an expression of the variation of the instantaneous power in relation to the average power. If a motor were operating with a constant load, the RMS power would be equal to the average power. In a beam pumping system the cyclical loading results in high peak currents which can momentarily exceed the motor's rated current by 100%. The severity of this cyclical loading is expressed by the cyclic load factor which is the ratio of the RMS power to the average power. A motor with a constant loading exhibits a CLF = 1.00. In a pumping system the CLF may range from 1.03 to 1.5 depending on the type of unit, the motor's characteristics, the counterbalance and the pumping speed.

- **RECOMMENDED MIN HP. (D)** is the power rating recommended for NEMA "D" motors used with conventional geometry pumping units and assuming a CLF of 1.375. In general NEMA "C" motors and multi-cylinder engines will require about 38% more horsepower rating. For Mark II units the rating may be reduced by about 20%. The NAMEPLATE HP RATING is read from the actual motor nameplate.

- **INPUT HP** is calculated from the measured electrical power including credit for generation. It represents the power supplied to the motor during one pumping cycle. The ratio of the polished rod horsepower to the input horsepower is a measure of the overall efficiency of the pumping unit, motor and surface equipment. Surface efficiency can only be calculated if a dynamometer measurement has been performed.

- **APPROXIMATE OUTPUT HP** is computed from the input horsepower using an average motor efficiency of 85%. The reason that it is labeled "approximate" is that the motor's efficiency varies in relation to the motor's speed and depends greatly on the type of motor that is used. Type "D" motors exhibit greater and more uniform efficiency that Ultra High Slip motors.

- **AVERAGE KVA** is calculated by multiplying the voltage value entered in the well file by the average current for a pumping cycle and dividing by 1000.

- **AVERAGE KW** is obtained by integrating the measured consumed power as a function of time over one pumping cycle and dividing the area by the time elapsed for one stroke. When generation credit is considered the measured generated power is subtracted from the consumed power.

- **AVERAGE POWER FACTOR** represents the fraction of power that is doing useful work to the total power used by the motor (the difference corresponds to the heating losses due to the magnetization current) It is the ratio of the AVERAGE KW to the AVERAGE KVA.

The pumping speed is expressed as **STROKES PER MIN** and is computed when the software identifies the time between the maximum power peaks that occur in two adjacent strokes. The most recent production well test data is obtained from the well file and is presented as **BOPD** and **BWPD**.

EFFICIENCY PARAMETERS

Due to the cyclic nature of a beam pumping installation, instantaneous efficiency of system components is constantly changing during a pump stroke. To get the average efficiency, instantaneous measurements at several points in the stroke must be obtained. Average motor efficiency, surface efficiency, and total system efficiency can all be effective in evaluating lifting performance.

Average motor efficiency can be calculated if motor input power measurements and motor performance data are available. The integral of the output power (area under output power curve for a stroke) divided by the integral of the input power will yield the average motor efficiency for a stroke. This quantity will account only for losses in the motor.

The total surface system efficiency (motor, belts, gear reducer, pumping unit) is obtained by dividing the polished rod power by the motor input power. Motor input power per stroke and dynamometer measurements are thus necessary to determine surface efficiency. Surface efficiency accounts for losses in the motor, belt drive and pumping unit.

Downhole efficiency must be estimated by comparing the pump power calculated from the downhole dynamometer to the polished rod horsepower. The accuracy of this parameter is dependent on the assumptions and the method used in converting the surface dynamometer data to the calculated pump displacement. The preferred method for pump power calculation is to use the product of flow rate times the difference between intake and discharge pressure.

Total system efficiency is determined by dividing pump output power by motor input power. Again, motor input power measurements and dynamometer data are necessary. Calculation of the power developed at the downhole pump is made by computer simulation of the rod string dynamics. This yields pump displacement and load and thus power at the pump. Surface losses and downhole losses are reflected by total system efficiency.

Efficiency measurements are useful in identifying high operating cost components of a beam pump system. For example, a well may have a relatively high lifting cost due to a low average motor efficiency, high mechanical losses in the pumping unit, significant rod/tubing friction, or many other problems that can be identified by analyzing efficiencies.

Work per Unit Volume

This quantity expresses the amount of energy required to lift a given volume of fluid. The volume that is considered may be the gross fluid volume or the net oil volume. It is only applicable to comparisons where conditions from well to well include similar productivities and similar depths. The produced volume should be obtained from a recent and accurate well test. A reasonable substitute is the produced fluid calculated from pump displacement estimated from the pump dynamometer card. This is of course dependent on the accuracy of the computer program used to calculate the pump travel.

Work per Unit Volume per Net Lift

In order to be able to compare the efficiency of wells producing from different depths or having different productivities which result in different draw downs it is possible to normalize the energy used to the net lift. For accuracy this requires measurement of the annular fluid level from an echometric survey.

Work Per Stroke

Kilowatt-hour per stroke is a simple efficiency indicator which should be used for comparing wells with very similar operating parameters. It can be especially useful when comparing different operating parameters for the same well when the stroke length is not changed. An example of this would be the analysis of different motor torque settings for a well. A dynamometer analysis is not necessary to generate this indicator. KWH per stroke does not consider the effect of over travel; therefore, it is more applicable to less elastic (i.e. steel) rod strings. KWH per stroke does not normalize for differences in net lift, specific gravity, or tubing/casing pressure. Normalization for differences in stroke length can be achieved by considering a "standard" stroke length, for example 100 inches, and normalizing to this value. An analysis of electrical efficiency of various motor torque modes indicates the utility of the KWH per stroke indicator as will be discussed later.

FIELD TESTS

The objective of the field tests was to develop methodology that would allow reduction of beam pumping operating costs by effecting changes in operating conditions. Recognizing that each well and pumping system performs as a unique system, the ideal solution would be to test every well in a given field and optimize its mode of operation. An operator with a large number of wells cannot do this because of time and manpower constraints. A compromise is to measure as many wells as possible, selecting those that are representative of the majority of the wells in the field, and use these results to make wholesale changes in operations. This will hopefully permit improving the performance of the majority of the wells.

Performance analysis of the wells tested included measurements with a calibrated dynamometer data acquisition system and the power measurement system described earlier. Data was then processed using three different dynamometer analysis programs to obtain down-hole dynamometer cards. It should be noted that the three programs gave slightly different results, however the conclusions derived in this paper would be the same regardless of which program's results would have been used.

Well and Pumping Unit Descriptions

The wells selected for the study have an average depth of about 5000 feet and are completed in the same formation. Typically the pump setting depth varies from 4850 to 4950. Production ranges from 250 to 500 barrels per day of total fluid. Only conventional, crank balance pumping units have been included in the study, of types C320-213-120, C320-256-100, C456-256-120, and C640-356-144. All wells were outfitted with steel rods, except one. Most wells are equipped with Ultra High Slip motors.

Test Matrix

The tests were designed to limit variation of parameters to a minimum while obtaining the maximum information. A total of eleven wells were tested. The test matrix resulted in a total of 80 test cases. Data acquisition required approximately three weeks and involved one engineer one production technician and one electrician. Work crews were necessary only for tests involving changes in counterbalance.

Operating parameters were varied as follows in all wells tested:

- Torque level of motor: High, Medium, Low
- Direction of Rotation: Clockwise, Counterclockwise

On selected wells variations were made of the following parameters:

- Counterbalance effect.
- Tubing Back pressure
- Stuffing box friction

In addition in two wells the Ultra High Slip motor was replaced with a NEMA-D motor and the well was re-tested.

The logic for these selections was to study the effect of those parameters that could be easily changed with a minimum of manpower and equipment. For this reason changes in operating conditions such as stroke length or pumping speed were not considered practical.

RESULTS AND DISCUSSION

The results indicate that in general each well tested exhibited a characteristic performance slightly different from that of the other wells tested. In spite of this it was possible to establish general trends which can be applied to wells in this particular field.

Effect of Direction of Rotation and Torque Mode

Results indicate that changing the torque mode of the UHS motors, and the direction of rotation can have a significant effect on the efficiency of the pumping system in some wells while in other wells there seems to be less sensitivity to these two parameters. Figures 3,4 and 5 show the effect of these two parameters on the efficiency expressed as energy required to lift one barrel of fluid per 1000 feet. Net lift was calculated as described earlier. Also shown on the figures are the corresponding torque reducer loading as percentage of rated capacity. The well in Figure 3 exhibits the most efficient mode when run in the high torque mode in the clockwise direction (HIGHCW) and shows that efficiency is affected significantly (from 0.32 to 0.18 KWH/Bbl/1000 ft) This well is equipped with a 404T motor. The well in Figure 4 (also a 404T motor) shows the best performance for low torque and clockwise rotation, but is less sensitive (0.29 to 0.24) while the well in Figure 5, equipped with a 445T motor, shows practically no variation in electrical performance. In all cases there were variations in the reducer loading, with increases corresponding to the higher torque modes and clockwise rotation. This is expected since the higher torque modes correspond to reduced motor slip. Analysis of the complete data set resulted in the conclusion that the wells equipped with the 404T motors performed on the average better in the high torque mode, With the 445T motor the low torque mode was better on the average.

Figure 6 shows the effect of direction of rotation on the measured dynamometer curves and the calculated torque curves for a C640-365-144 unit powered by a 445T motor in the high torque mode. Notice that there is a significant difference in both the dynamometer and the torque curves. In the Counter clockwise mode the loads and torques that are developed are lower that those observed when the unit is operated in the clockwise direction.. The torque peaks are also sharper in this direction, the gearbox is slightly overloaded and he corresponding operating cost was \$ 0.072 per gross barrel of fluid pumped while the cost was \$ 0.057 for the opposite direction of rotation.

It is important that the reader does not conclude that all units should be operated in the counter clockwise direction. The results vary greatly from unit to unit. The logical conclusion is that direction of rotation may be an important parameter in determining operating conditions and that it may be advantageous to test the effect of reversing direction. This is something that, for a qualified electrician, will take only a few minutes.

Effect of Counterbalance and Tubing Back Pressure

Figure 7 shows that the effect of these two parameters on lift efficiency can be significantly greater than the effect of torque mode and direction of rotation. The best performance was obtained in low torque in the clockwise direction, with the counterbalance as existing in the well at the time of the test. The tubing back pressure was increased from 200 to 600 PSI which caused an increase in energy consumption to 0.38 KWH/Bbl/1000 ft.

The back pressure was reduced to 280 PSI and the counterweights were moved so as to achieve a balanced condition (upstroke power peak equal to the downstroke power peak) This resulted in a power use of 0.26 which is close to the original value. The counterweights were then moved so as to cause a significant under balance. The power use increased to about 0.32. Similar results were obtained in a second well equipped with a C320 unit.

The effect of changes in counterbalance on the dynamometer and torque curves is shown in Figure 8 for a C640-365-144 unit operating at 11.3 strokes per minute in the clockwise direction and driven by a 445T motor in the low torque mode. the gear box torque is reduced significantly when the unit is balanced so that the upstroke and downstroke torque peak at the same level. The pump cards are nearly identical while the polished rod dynamometers show minor differences with nearly the same horsepower: 14.9 balanced vs. 14.8 unbalanced. The efficiency of the unit is greatest for the balanced condition with a cost of \$ 0.0505 per gross fluid barrel vs. \$ 0.0575 unbalanced. Thus the balanced unit delivers more polished rod horsepower for less electrical cost. In general this behavior was observed in most of the units tested.

Effect of Motor Sizing

Figures 9 and 10 show the results of changing the motor in two wells, from Ultra High Slip (404T) to properly sized NEMA-D motors. It can be seen that in both cases the units powered with the NEMA-D motors exhibited a lift performance which was comparable to selecting the high torque mode in the UHS motors. This is the expected result since they have comparable slip. The reducer load increased correspondingly.

For the ultra high slip motors the effect of torque mode on the dynamometer cards is shown in Figure 11. High torque and medium torque exhibit the highest polished rod loads and the fastest pumping speed 6.6 SPM in this C456-256-120 unit driven by a 404T motor. Figure 12 shows the corresponding calculated torque curves. Notice that the unit is somewhat rod heavy and the gearbox is overloaded in the high and medium torque modes. On the other hand the high toque mode is the most efficient as shown by the following table:

	PRHP	Monthly cost \$	\$/GBFL
Low Torque	10.4	370	0.0571
High Torque	11.9	217	0.0293

Thus the high torque mode delivers 14.4% more polished rod horsepower for 41.4% less electrical cost. This is explained by the fact that in the low torque mode the speed variation over a stroke is such that the motor operates longer in the region of low motor efficiency while in the high and medium torque modes the speed remains closer to the high efficiency region.

Efficiency Parameters

As discussed earlier it is possible to use various efficiency parameters in order to characterize the performance of the pumping system. Ideally one would like to determine the efficiency of the various components or at least evaluate separately the efficiency of the surface system and that of the downhole components. This requires measurement of the power input AND an accurate dynamometer card. Figure 13 shows the result of such analysis for the well discussed earlier in Figure 7. It can be seen that the efficiency correlates well with the lift performance. The two worst lift performances (unbalanced well and high tubing pressure) correspond to the lowest surface and overall efficiencies. In addition it can seen that the two efficiency curves are practically parallel. This is an indication that the downhole efficiency is practically constant and insensitive to the variations in surface operating parameters.

Eliminating the need for dynamometer measurements would greatly reduce the work load to identify wells which are not operating at acceptable levels of efficiency. An efficiency parameter which was found to provide this diagnostic capability is the power cost per stroke. This quantity is more conveniently expressed as cost per 1000 strokes of a standard length (100 inches) as a means of taking into consideration variations in surface stroke. Figure 14 shows a plot of operating cost per gross fluid barrel pumped as a function of the $/1000 strokes of 100 inches for all the tests in this study. It can be seen that a good correlation exists indicating that by measuring the power use, stroke length and pumping speed of a unit it is possible to identify whether it is operating at an average cost (in line with other wells) or at an excessive cost. This measurement can be undertaken by a properly trained technician with a minimum of time. Having identified the out-of-norm wells, these can be fully tested as recommended.

Examining the data for the well discussed in Figures 11 and 12 it can be seen that $/1000 strokes correlates quite well with operating cost, as shown by the following table:

	$/GBFL	$/1000 Strokes
Low Torque	0.0571	1.435
Medium Torque	0.0457	1.209
High Torque	0.0293	0.762

the importance of this observation is that in order to determine the $/1000 strokes all that is required is a measurement of the power consumption in order to establish the most efficient mode of operation.

CONCLUSIONS

The results of this study indicate that for the wells tested it was determined that significant variations in efficiency are to be expected even in a field where wells have been producing under similar conditions. As seen in Figure 10 lifting cost can vary by a factor of almost 3.5, depending on the selection of motor torque setting, direction of rotation, tubing back pressure and level of counterbalance.

A detailed study of these effects indicated that it is possible to characterize the effect of these variables by studying a representative subset of the wells so as to be able to improve the performance of the majority of the wells in a large field. This presumes that a degree of similarity exists in terms of the types and sizes of pumping units, pump setting depths, sucker rods, etc.

Accurate measurement of instantaneous power use during a pump stroke is a simple and effective method to determine the electrical and mechanical efficiency of a pumping system.

NOMENCLATURE

HIGHCCW -	High torque mode, counter clockwise.
HIGHCH -	High torque mode, clockwise.
MEDCCW -	Medium torque mode, counter clockwise.
MEDCW -	Medium torque mode, clockwise.
LOWCCW -	Low torque mode, counter clockwise.
LOWCW -	Low torque mode, clockwise.
LOWCW/B -	Low torque mode, clockwise, balanced unit.
LOWCW/U-	Low torque mode, clockwise, unbalanced unit.
LOWCWHP-	Low torque mode, clockwise, high tubing pressure.
CCW NEMA-D-	Counter clockwise, NEMA-D motor.
CW NEMA-D -	Clockwise, NEMA-D motor.

CCWB NEMA-D-Clockwise, balanced unit, NEMA-D motor.
CCWU NEMA-D-Clockwise, unbalanced unit, NEMA-D motor.
CCWH NEMA-D-Clockwise, high tubing pressure, NEMA-D motor.
HISBCCW - High stuffing box friction, counter clockwise.

Motor Characteristics

445 T Frame
- Type - P
- HP - 72/49.5/39.3/30.5
- Ins Class H
- RPM - 1000/955/900/830
- 460 V
- Amps - 95/74/61/50
- 3 Phase, 60 Hz

404T Frame
- RPM - 1200
- % Torque 100/70/40
- Amps - 48/35/25
- 460 V, 60 Hz

NEMA- D motor
- RPM - 1115
- HP - 30
- Volts 460/796
- Amps 36/21
- 3 Phase
- 60 Hz

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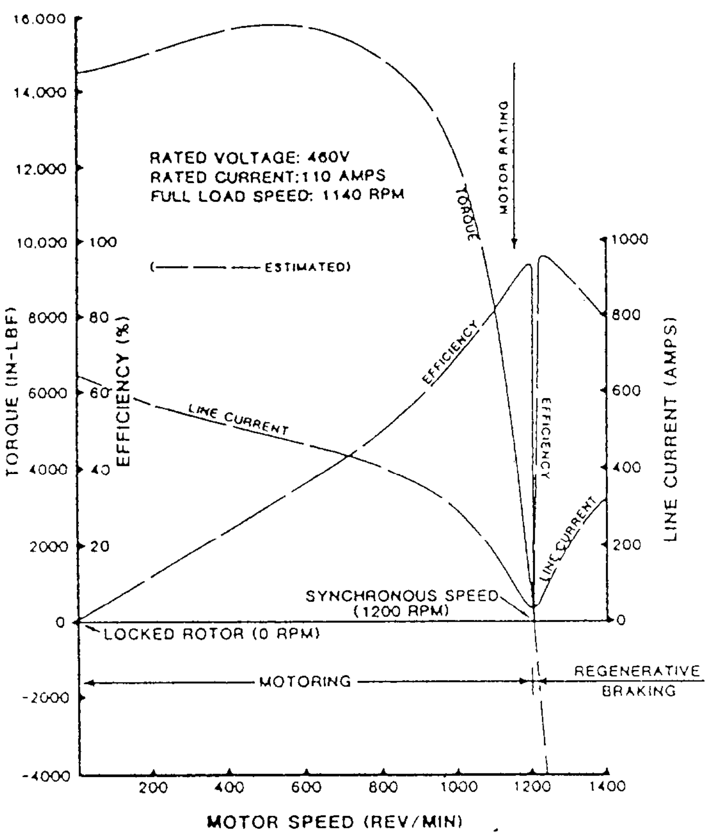

Figure 1 - Performance curves for a
100 HP NEMA-D motor
(after Gibbs, SPEPE August 1987)

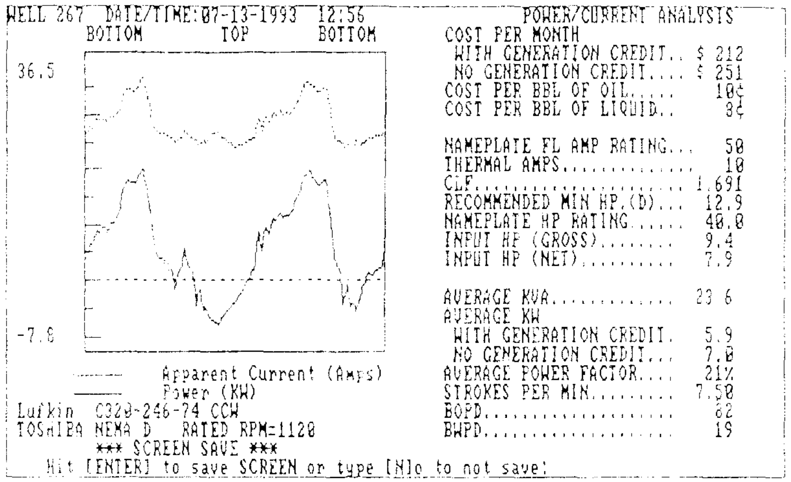

Figure 2 - Screen display of instantaneous motor power and current for one pump stroke.

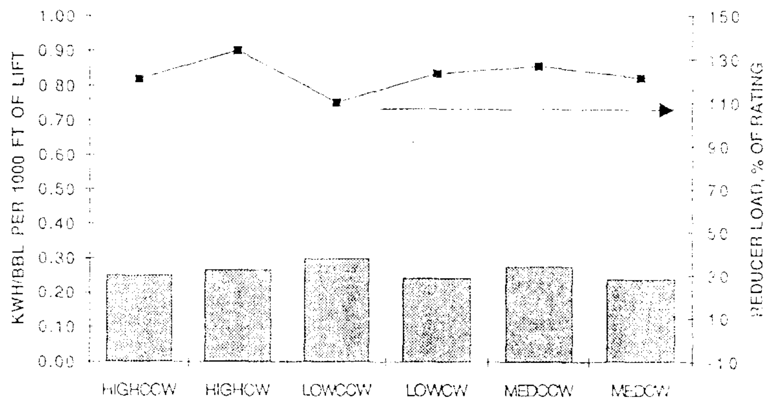

Figure 4 - 320-256-100, 404T

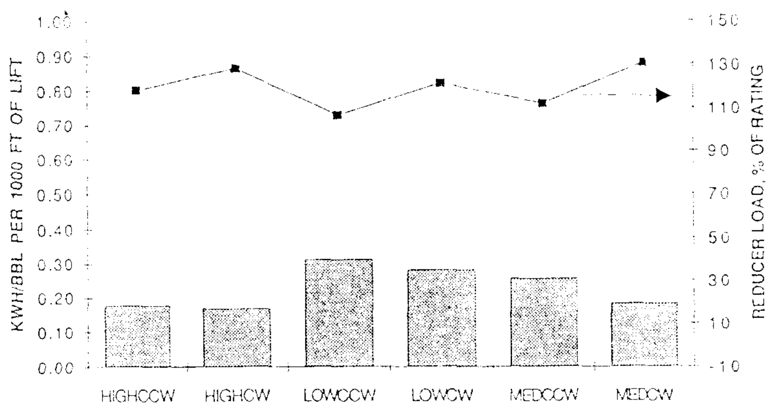

Figure 3 - 456-256-120, 404T

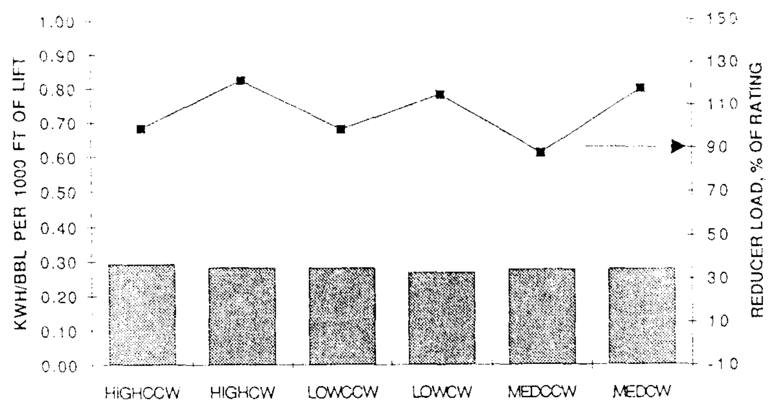

Figure 5 - 640-365-144, 445T

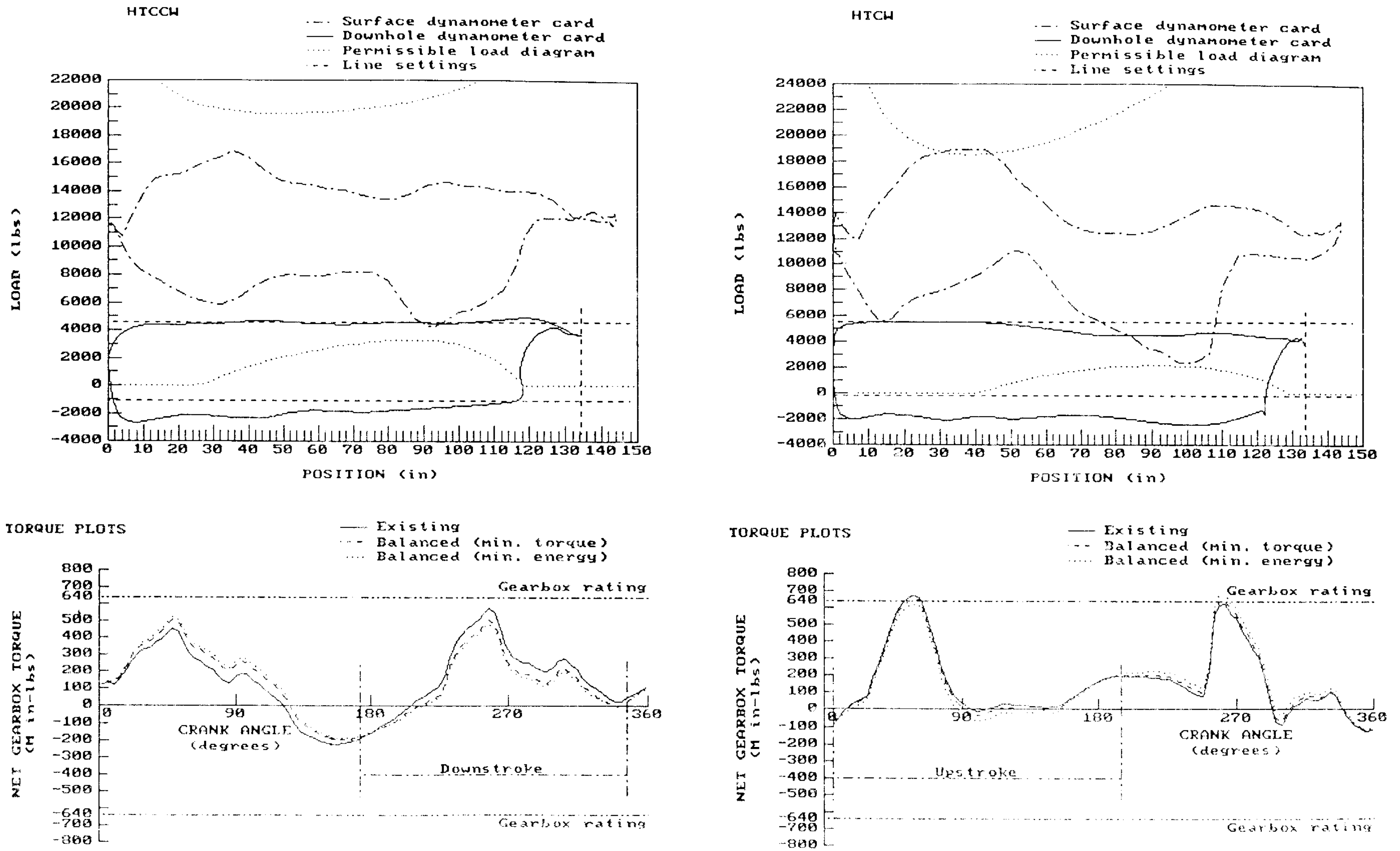

Figure 6 - Effect of direction of rotation on dynamometer and torque curves
C640-365-144 with 445-T motor

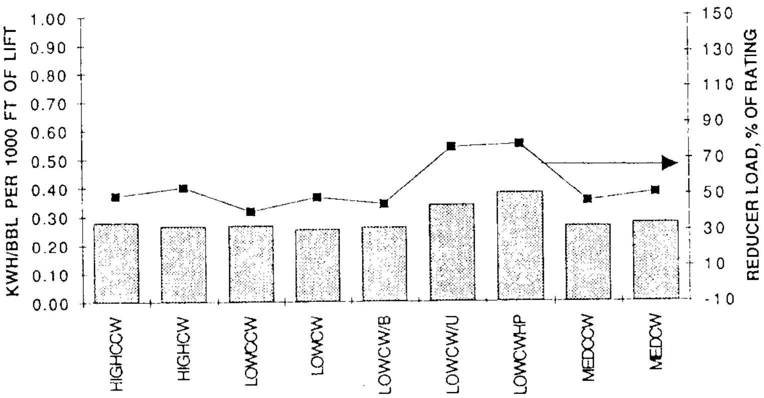

Figure 7 - 640-356-144, 445T

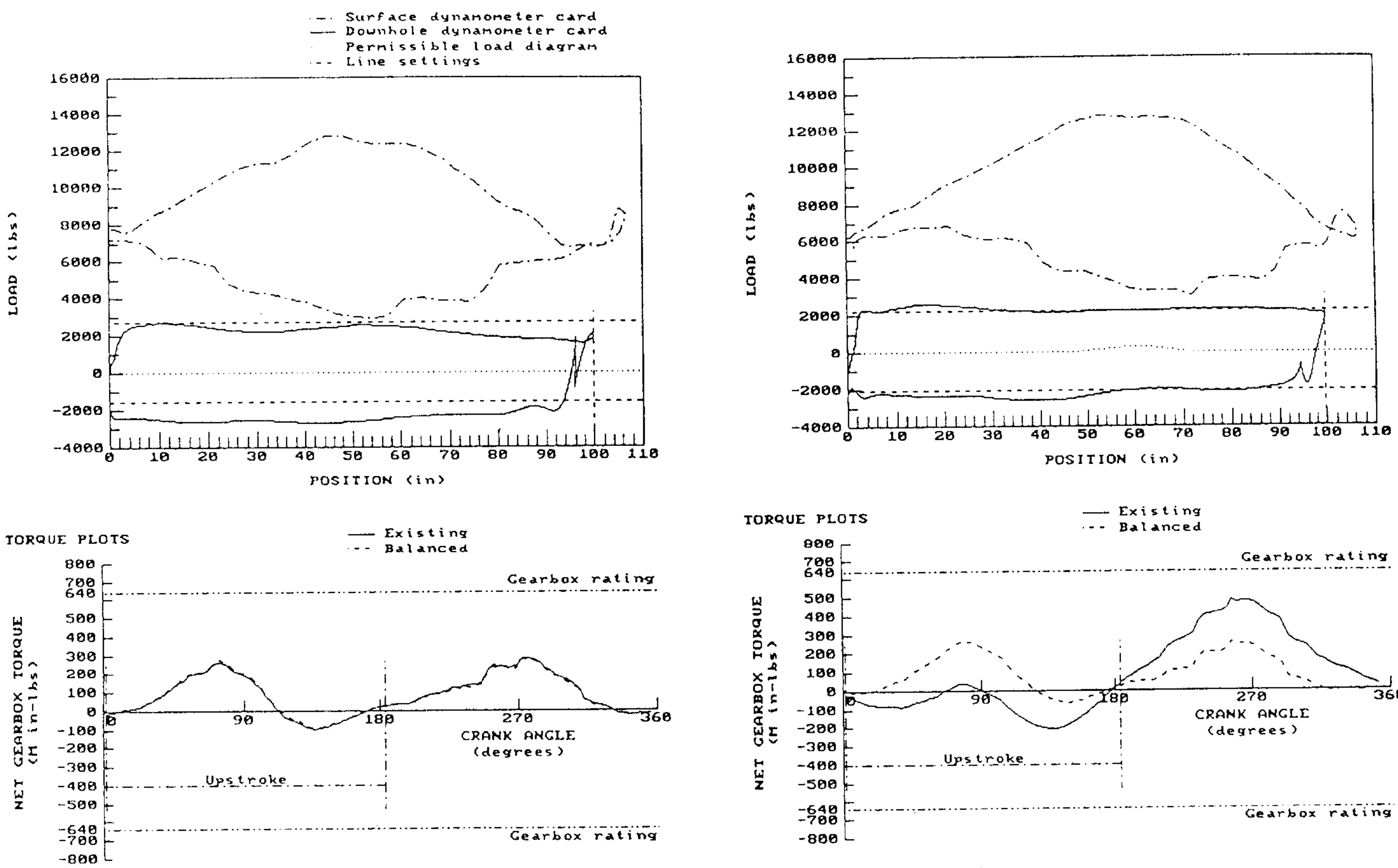

Figure 8 - Effect of counterbalance adjustment on dynamometer and torque curves.
C640-365-144 with 445-T motor.

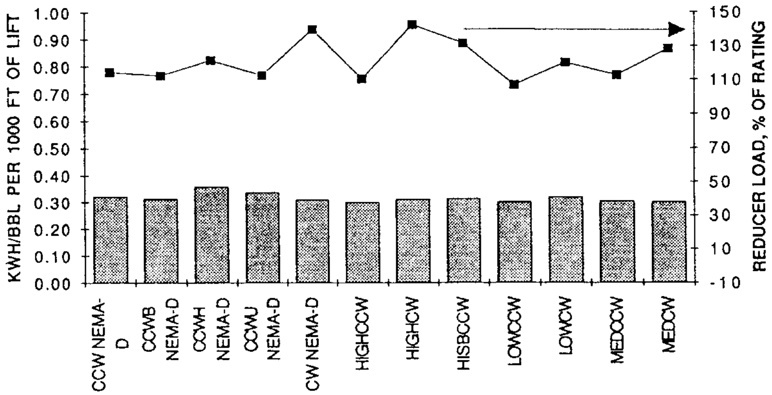

Figure 9 - 320-213-120, 404T

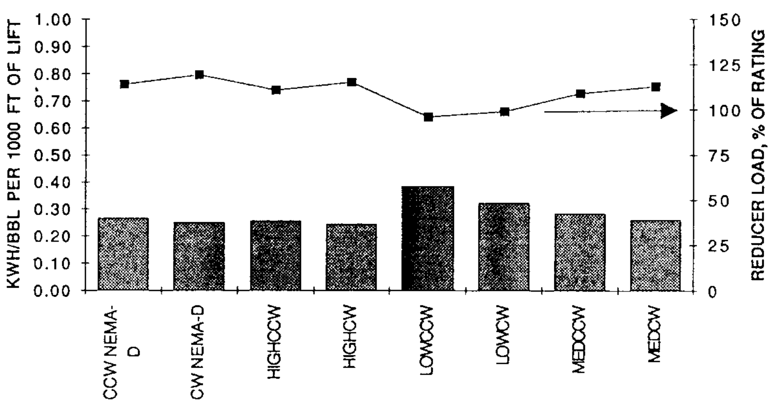

Figure 10 - 456-256-120, 404T

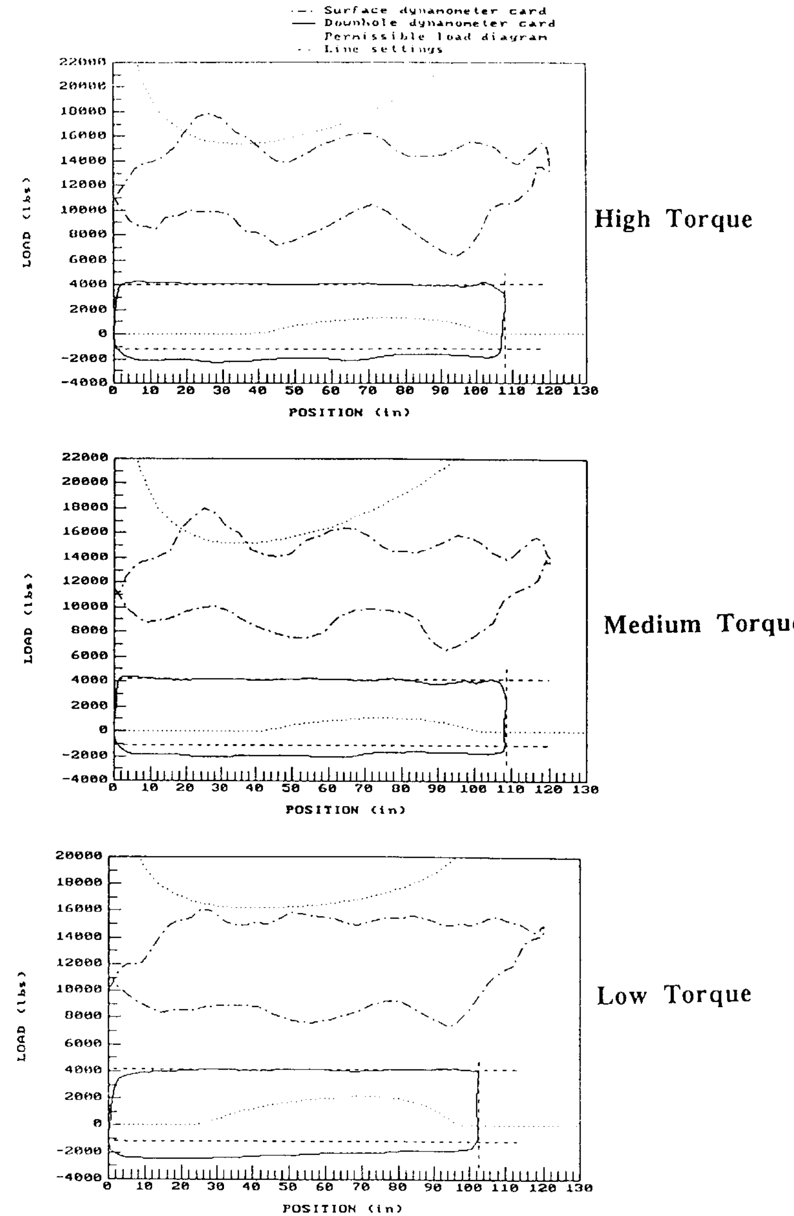

Figure 11 - Effect of torque mode on dynamometer and torque curves. C456-256-120 with 404-T motor.

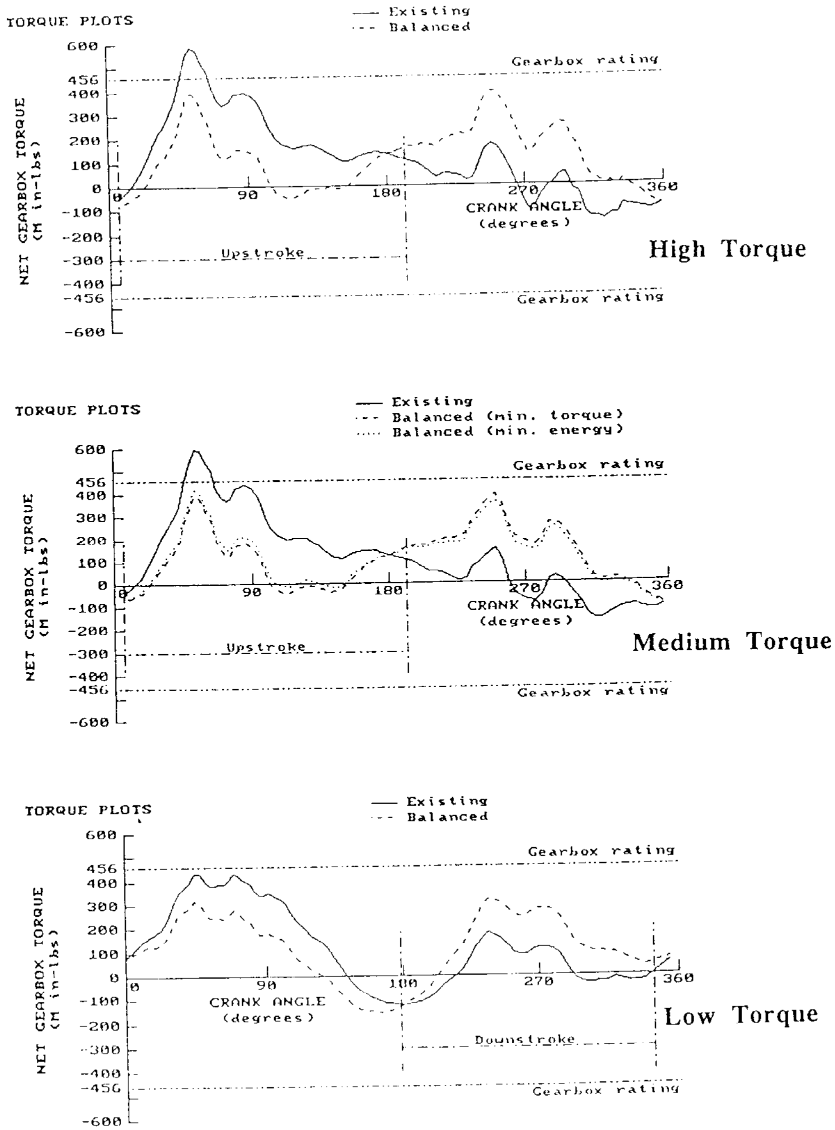

Figure 12 - Effect of torque mode on dynamometer and torque curves.
C456-256-120 with 404-T motor.

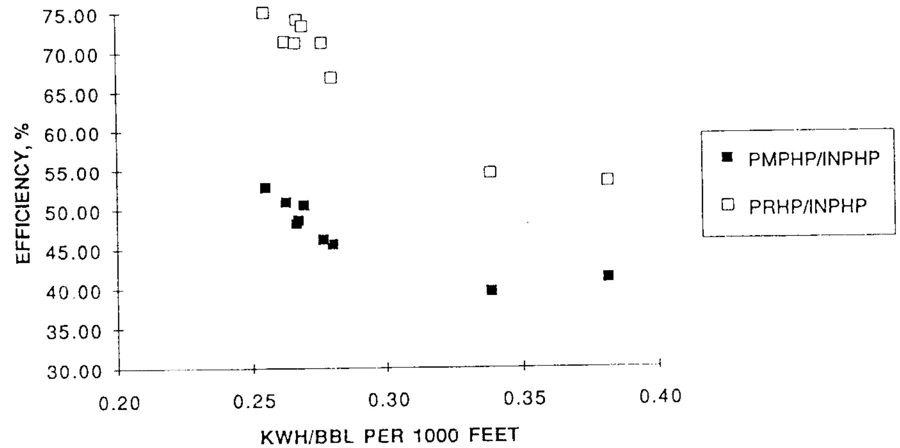

Figure 13 - Efficiencies for well in Figure 7.

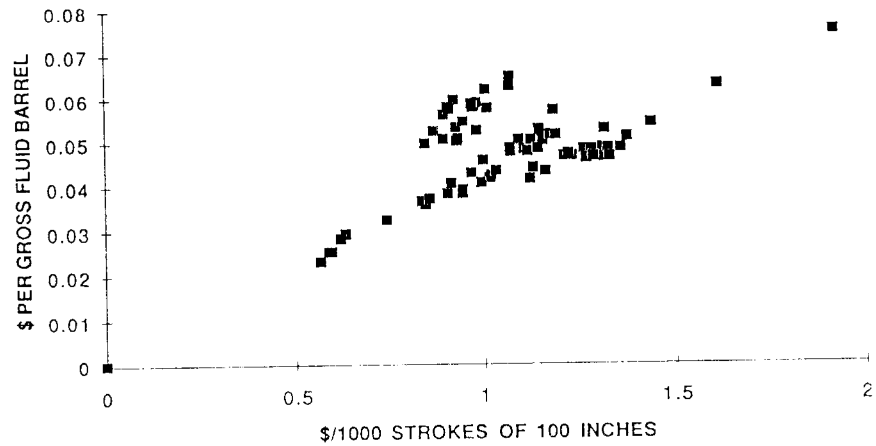

Figure 14 - Efficiencies for all wells and all cases.