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Motor Power/Current Measurement for Improving Rod Pump Efficiencies

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ABSTRACT

The development of accurate digital measurement of instantaneous power during a pump stroke has made possible a very quick and detailed analysis of the efficiency of the pumping system. The efficiency is then used as the benchmark for determining whether a complete well performance analysis is warranted from the standpoint of making best use of personnel and economic resources to increase oil production.

In addition, power measurement provides direct information about lifting cost per barrel of fluid and barrel of oil produced, electrical and mechanical loading of the prime mover, peak power demand, power factor and minimum required ratings. These results give operating personnel information regarding potential problems and give to management a complete picture of the distribution of pumping costs.

The power measurements are also converted, by the software, to instantaneous torque and presented as continuous torque curves for the upstroke and downstroke. This allows determination of the existing level of counterbalance and provides the most rapid and accurate method for counterbalance adjustment to achieve lower torque loading on the gear box and reduced energy utilization. One of the principal advantages of this balancing method is that counterbalance adjustment can be made without need for an accurate description of the pumping unit's geometry which is often unknown or inaccurate. The effect of counterweight displacement on torque and power is observed immediately by repeating the power measurement after relocating the counterweights.

This paper presents a series of case studies showing the application of power measurement to a variety of pumping systems and components, including conventional, Mark II, Rotaflex units and high efficiency motors.

INSTANTANEOUS MOTOR 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. [(1)]

Special purpose integrated circuits process the sensor 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 oil disk for subsequent printing.

Figure I 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 fight. Thus the first half of the plot corresponds to the up-stroke and the second half to the downstroke. 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 operation at the specified run time and based on the cost per KWH and kW demand 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. 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 or the dynamometer test was not representative of average conditions.

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, motor/pump efficiency and total system efficiency can all be effective in evaluating lifting performance. [2-14]

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 surface 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.

The motor/pump efficiency is defined as the pump power divided by the net input motor power. The pump power is calculated from the pump dynamometer card which is computed from the measured surface dynamometer using the wave-equation model and assumptions about energy losses due to viscosity and friction. The pump power can be compared to the surface polished rod power as an aid to analyze downhole efficiency.

The calculation of total system efficiency requires determination of the hydraulic work required to lift the produced fluids from the effective liquid level depth. The effective liquid level depth is determined from the producing bottomhole pressure and the average produced liquid gradient. An acoustic liquid level depth measurement and casing pressure measurement are performed to determine the producing bottomhole pressure. The value of the producing bottomhole pressure is divided by the average gradient of the produced liquid to determine the height of the column of liquid being supported by the bottom hole pressure. The effective liquid level depth is equal to the formation depth less the height of the column of liquid supported by the producing bottom hole pressure. The ratio of the hydraulic work divided by the net motor input work is defined as the total system efficiency. This value accounts for the losses in the

motor, belts, pumping unit gear box, pumping unit bearings, rod string, liquid viscous losses, tubing back pressure, and stuffing box friction, and other losses.

Please note that if the operator increases the tubing pressure which will increase the net input motor power and the pump power, the motor/pump efficiency may improve; but, the production from the well will probably be reduced while the motor input power will increase thus reducing the total system efficiency. The total system efficiency is necessarily less than the motor/pump efficiency described earlier since the lifting friction losses, stuffing box friction losses and tubing pressure losses are not considered in the motor/pump efficiency. While motor/pump efficiencies are reported in the mid 50% range, a total system efficiency in the mid 40% range is a good value for most beam pumped wells. Usually the total system efficiency can be determined more accurately than the motor/pump efficiency. For comparison purposes between beam pump, ESP, PC, Rotaflex and other pumping systems, the total system efficiency is the most appropriate measurement for a fair comparison.

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, high tubing pressure or many other problems that can be identified by analyzing efficiencies.

The efficiencies of the surface unit, motor/pump and overall system are calculated from power measurements. load measurements and well data. Note that these efficiencies can be determined from work or power, where power is the rate of performing work. For example, the electrical work input into the pumping unit motor for a 24 hour period could be expressed as KWH. The work performed by the pumping system would be the total weight of the produced liquid multiplied by the net lift over the same 24 hour period. This would allow determination of overall system efficiency using net work performed compared to the net work energy input into the motor. However the surface dynamometer and the pump cards are normally analyzed in terms of horsepower.

The average input power to the motor can be determined by averaging instantaneous power measurements over one complete pumping unit stroke. The hydraulic horsepower required to lift the produced fluid from the net depth can be calculated using the total weight of liquids produced, the net lift depth and the period of time over which the liquids are produced. The two approaches are equivalent. For ease of analysis using conventional techniques, the power has been utilized, instead of work, to determine efficiencies of the various components.

PUMPING UNIT BALANCING

Accurate balancing of beam pumping systems has been greatly simplified by the development of sensors for acquisition of instantaneous electrical power used by the prime mover and of software to analyze the counterbalance effect. The new software, not only determines the existing balance condition but also gives to the user the distance that the counterweights must be moved in order to achieve the optimum balance.

Balancing a pumping unit requires that the torque at the gear reducer be determined as a function of position during a complete pump stroke. Three practical methods have been developed:

Measure the load vs. position at the polished rod (dynamometer card) then measure the counterbalance effect at the polished rod and then compute the torque at the gear reducer from a knowledge of the geometry of the unit.

Measure the load and position at the polished rod and measure the position of the counterweights on the cranks. Then calculate the present gear box torque and the new positions for the counterweights for proper pumping unit balance using the geometry of the pumping unit.

Measure the power used by the prime mover and convert the power to torque.

The first method suffers from complications caused by inaccurate description of the beam pump geometry, the difficulty in measuring the counterbalance effect at the polished rod, and the need to convert the computed desired counterbalance effect to actual repositioning of the counterweights.

The second procedure requires identification of the counterweights and cranks and determination of the weight of each component. The position of the counterweights must be measured. This data along with a surface dynamometer card and geometry of the pumping unit are used to calculate the new location of the counterweights for achieving balance of the pumping unit.

The third method eliminates these problems by direct measurement of electrical power (kW) at the motor as a function of time during a pump stroke using newly developed power sensors that arc connected to the switch box. The software acquires the power data and then calculates the torque at the gear reducer.

Recalling that in a rotating system the instantaneous power is given as the product of torque times rotary speed, it can be seen that the instantaneous torque can be calculated from direct measurement of the power and the speed of rotation:

$$Torque = 84484 \times Eff \times \frac{kW}{SPM}$$

where torque is given in inch-pounds.

The efficiency *(Eff)* of power conversion by the motor and power transmission through the belt drive and the gear reducer varies with each installation and the loading of the system. In general it decreases as the loading decreases. For a normally loaded and properly installed system the efficiency is estimated at 80%. However because of the uncertainties in this quantity, the user is allowed to enter a value which more closely fits the particular installation. The calculation also requires the knowledge of the instantaneous crank speed. In the calculation this quantity is assumed to be constant and directly related to the pumping speed (SPM) which is automatically determined by the program from the power data.

Figure 2 shows typical torque analysis output from the program. On the left half of the screen are plotted two torque curves as a function of time: the solid line corresponds to the calculated actual torque while the dotted line corresponds to the torque that would be observed if the unit were counterbalanced in such a way that the peak upstroke torque is equal to the peak downstroke torque. Note that the negative torque corresponds to the portion of the stroke where the gear reducer is driving the motor into the generation region.

On the right, the tabulated torque analysis gives the **UPSTROKE PEAK** and the **DOWNSTROKE PEAK** torque values in thousands of inch-lb. that occur during the stroke. The difference between these values is a measure of the unbalance of the system. If the upstroke peak is greater, the unit is underbalanced or “rod heavy”. If the downstroke peak is greater, the unit is overbalanced or “crank heavy.” In this case the unit is greatly overbalanced with the upstroke peak of -179,000 inch pounds and the downstroke peak of 272,000 inch pounds. Note that during the upstroke the negative torque peak is larger than the positive torque peak on the gearbox. The torque that would be experienced if the counterbalance were adjusted so that two peaks were equal is displayed as the **BALANCED PEAK** value and is estimated at 188,000 inch pounds.

The utilized value of **Eff** (the ratio of tile power input at the motor to the power delivered at the crank) and the calculated pumping speed SPM are also displayed.

The counterbalance change (**CB CHANGE FOR BALANCE**) is displayed in thousands of inch-lb. indicating whether it should be increased or decreased. In this case the software recommends a decrease in counterbalance of 84,000 inch pounds. This quantity is computed by the software assuming a constant pumping speed and superimposing to the actual measured torque an arbitrary sinusoidal torque adjustment of the same frequency as the pumping speed and in phase with the counterweights (180 degrees out of phase with the measured torque). The resulting torque corresponds to the torque that would be observed if the counterweights were moved on the crank a distance equal to the applied arbitrary torque divided by the weight of the counterweight. The software undertakes this trial and error calculation automatically by adjusting

the counterbalance in small increments until the recomputed upstroke and downstroke peak torque are equal. The resulting **Balanced Torque** is plotted on the figure using the dashed lines.

The analysis also indicates the distance and direction of the counterweight movement required to change the counterbalance by the indicated amount of torque. When multiple counterweights are to be moved. Then, all of the counterweights must be moved by the distance displayed by the program.

Knowing that the unit in the example well is equipped with four counterweights of 2662 lb. each for a total of 5324 lb. the program recommends a movement of 16 inches IN for both counterweights.

Note that it is not necessary to measure where the weights are located initially but only the distance that they are to be displaced from their present location. On the other hand it is very important to correctly identify the size of the counterweights that are installed on the unit. This permits the operator to enter the correct value (in pounds) of the counterweight(s) to be moved.

The principal assumption is that the speed of rotation is represented by an average value during the pump stroke while in reality it could vary by as much as 5-40%. The user is allowed to input the percentage speed variation that corresponds to the type of motor being used. Speed variation is expressed as the ratio of minimum speed to average speed.

Balancing the unit will result in small increases in pumping speed from 1 to 5%. These changes may affect the dynamics of the sucker rods and modify the net pump stroke. After the counterbalance adjustment is completed it is recommended that a dynamometer test be undertaken in order to check that the desired pump displacement is obtained.

It is impossible to obtain consistent results if tile well is not pumping at steady state conditions or if it is pumped off. After each change in counterbalance a sufficient length of time should elapse before performing another balance test to insure that the well's producing characteristics have returned to normal.

Please refer to the Appendix for additional information about measured and calculated data shown in the power and torque analysis figures.

FIELD CASES

Figure 3 is a torque analysis for a conventional unit which is crank heavy. The torque should be decreased 157,000 inch-lb. Two counterweights are to be moved which total 6,360 lb. The two counterweight should be moved 25 inches IN toward the shaft. Figure 4 is a torque analysis after the counterweights have been moved. The peak torque has decreased from 317,000 to 198,000 inch-lb. Note that the pumping speed increased from 6.90 to 7.23 SPM The power consumption decreased from 11.7 kW to 10.4 kW after balancing the unit.

Gas Interference

PK23 in Table 1 is an example of a well having gas interference in the pump. Gas interference can cause very low efficiency when the interference is severe. Test No. 1 represents the well producing with a Poor-boy gas separator. The system was producing 21 BOPD and 41 BWPD while operating 18 hours a day. The total system efficiency was 39%, A decentralized gas separator [16] was installed and the well was re-tested which is shown in test 2. The new separator increased production, reduced run time and improved overall system efficiency to 49%.

Power Balancing

Well 26-9 is on a pump-off controller and operates 11 hours per day. It produces 17 BOPD and 19 BWPD On Table 1, test No. 3 are shown the power and efficiency data for this well in the unbalanced condition. Test No. 4 represents the balanced conditions. The calculated. polished rod power. pump power and hydraulic power were very similar for both balanced and unbalanced conditions. Note that additional power was required for the surface system in an unbalanced condition and that the surface efficiency is lower. Balancing the unit utilizing the instantaneous power measurements for calculating torque results in savings of electrical power and in reduced loading of the gear box. The pumping speed also increases in the balanced condition thus

increasing pump displacement. Oftentimes, the electrical demand power is also reduced. [15] Power consumption was reduced from 13.9 to 12.9 kW.

Rotaflex Pumping unit

A Rotaflex unit behaves differently than a conventional beam pumping unit. On a conventional beam unit. the polished rod velocity varies continuously during the stroke.
To balance the unit, the maximum torque near the middle of the upstroke is matched to the maximum torque near the middle of the downstroke. The polished rod of a Rotaflex unit has approximately constant speed on the upstroke and constant speed of the downstroke, with reversal occurring quickly at the top and bottom of the stroke. In this case the maximum torque on the upstroke occurs at the beginning of the upstroke. The maximum torque on the downstroke generally occurs when the traveling valve opens and the fluid load is transferred to the tubing. Torque oscillations which reduce in amplitude follow the initial maximum upstroke peak torque and downstroke peak torque. This can be clearly seen in Figure 5 which shows the torque computed from measured motor power. Rather than balancing the initial maximum upstroke peak torque with the peak torque on the downstroke, the average values of the torques should be matched. This assumes that the torque rating of the gearbox is not being exceeded. Remember that the maximum torque on the Rotaflex gearbox occurs at the beginning of the upstroke and generally at the opening of the traveling valve on the downstroke rather than at the middle of the upstroke and downstroke as on a conventional beam pumping unit. Matching the average torque values will result in less loading of the drive system and in lower electricity consumption since the motor will be operating in a more efficient range.

The torque curve in Figure 5 is computed with the equation displayed on the figure. The motor/reducer efficiency is assumed to be 80%. This Rotaflex unit operates at 3.83 strokes per minute but the shaft of the Rotaflex gearbox rotates 5.5 times faster than the polished rod strokes per minute. Thus, the speed variation of 5.5 shown in the denominator of the equation adjusts for the faster rotational speed of the gearbox. Since the unit is equipped with a NEMA B motor with a speed of 1180 RPM at rated load, the speed variation of the motor can be neglected.

In order to determine the proper counterbalance, the cursor on the torque screen is moved using the arrow keys to measure the average torque on the upstroke, giving a value of about 78,000 inch-lb. Locating the-cursor on the average torque for the downstroke gives a value of 42,000 inch-lb. indicating the unit is underbalanced The average torque difference is (78000-42000)/2= 18000 inch-lb. and corresponds to the change in counterbalance moment required to balance the upstroke and downstroke average torques. The Rotaflex unit has a 36 inch diameter sprocket giving a moment arm of 18 inches. Thus dividing the desired counterweight torque adjustment of 18000 inch-lb. by the moment arm of 18 inches, indicates that weights totaling 1000 lb. should be added to the counterweight box.

Figure 6 shows the torque analysis after adding the 1000 lb. to the counterweight box. Note that the average torque on the upstroke has been balanced with the average torque on the downstroke. The peak torque measured in a balanced condition is considerably less than lite gearbox rating of 320,000 inch-lb. This Rotaflex system has an overall efficiency of 60% which is relatively high for an artificial lift system.

Please refer to Test 5 on Table 1. This data was acquired before balancing. Power measurements were not available before balancing. Test No. 6 represents power and dynamometer measurements after balancing. The Rotaflex unit has an overall efficiency of 60% which is relatively high for an artificial lift system. A NEMA B multi-torque motor operating in the correct torque mode powers this pumping unit.

Defective Cross Yoke Bearing

Test No. 7 was obtained on a Mark II pumping unit with a defective cross yoke bearing. The surface efficiency is low indicating loss of energy in the surface system. The cross yoke bearing was replaced and Test No. 8 was performed. Note that the surface efficiency improved. Figures 7 and 8 represent the torque and power data analysis after the cross yoke bearing was repaired. The production rate of the well increased between tests No. 7 and Test No. 8 which increased the hydraulic power.

CONCLUSIONS

1- Instantaneous power measurements along with other measurements allow determination of component and overall system efficiency of an artificial lift system. This analysis greatly aids the operator in optimizing production and reducing operating expenses by identifying problem components.

2. Power measurements permit more accurate and easier balancing than motor current measurements or dynamometer techniques.

3. Power measurements can be used for bench marking wells which are operating at low efficiency and require additional study.

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APPENDIX

Motor Performance

The performance of an induction motor subjected to the cyclical loading of a beam pumping system is described byvalues 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 multicylinder 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.**

The Speed Variation can be approximated by observing the motor current data and having knowledge of the full-load motor current rating and the slip of the motor at full load. Most motors are oversized for the unit they are driving and operate at full load only at the maximum load during the upstroke or downstroke. The speed variation can be estimated as 0.9 for loaded conventional NEMA (D) type motors and values ranging from 0.6 to 0.8 for high slip motors operating near peak load conditions.

Table 1

Test Number	Well ID	Net Input Power		Polished Rod Power, HP	Surface Efficiency	Pump Power HP	Pump/Motor Efficiency	Hydraulic Power, HP	Total System Efficiency
		KW	HP						
1	PK23	10.1	13.6	9.1	67	7.9	58	5.3	39
2	PK23								
3	26-9	7.7	10.3	8.1	78	6.7	65	4.4	43
4	26-9	7	9.4	7.9	84	6.6	70	4.4	47
5	2323	10.1	13.6	9	69	7.9	58	3.75	37
6	2323	11.1	14.9	13.1	88	11.9	80	7.3	49
7	3308			15.2		11.7			
8	3308	15.2	20.4	13.9	67	10.4		12.2	60
9	4113bfr	17.5	23.5	15.4	66	13	55	9.6	41
10	4113aftr	14.2	19.1	14.7	77	13.9	73	13	68
11									
12									

1 - Poorboy gas separator with gas interference.
2- Decentralized Gas Separator.
3- Conventional unit out of balance (cranck heavy)
4- Conventional unit in balance
5- Multitorque 48-35-25 Amp. in 35 amp. connection
6- Premium efficiency NEMA B, 30 HP motor
7- Rotaflex, out of balance, 50 HP motor.
8- Rotaflex in balance, low slip 60/50/34/25 motor.
9- Mark II with bad beam bearing
10- Mark II with repaired bearing

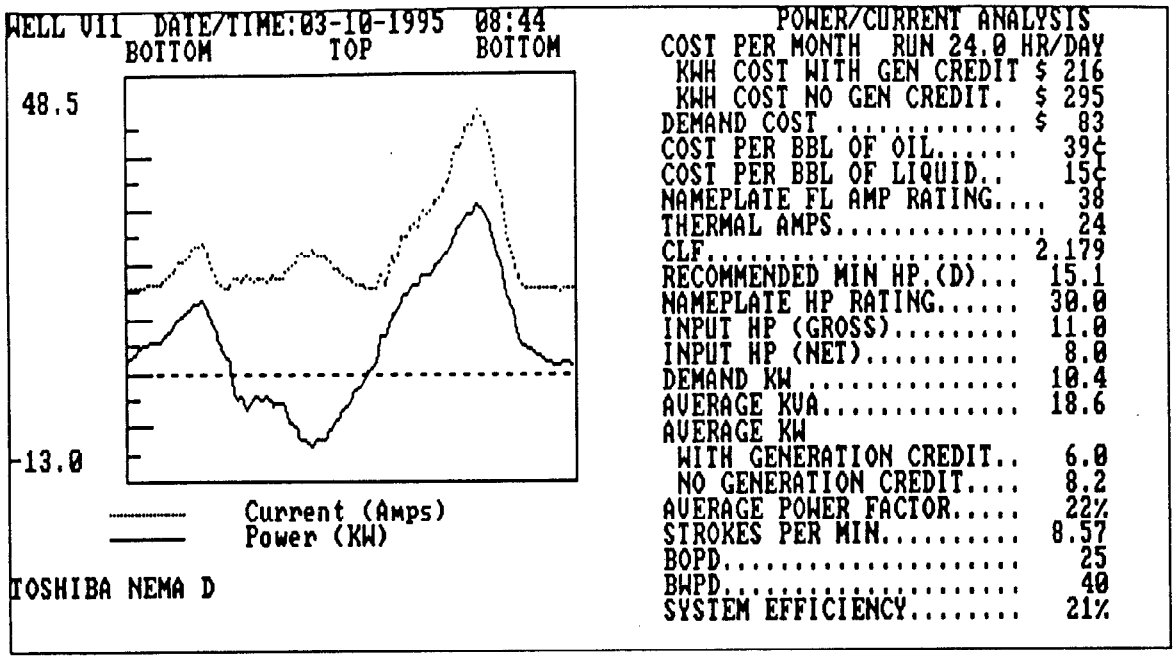

Figure 1 - Instantaneous Power Data and Analysis

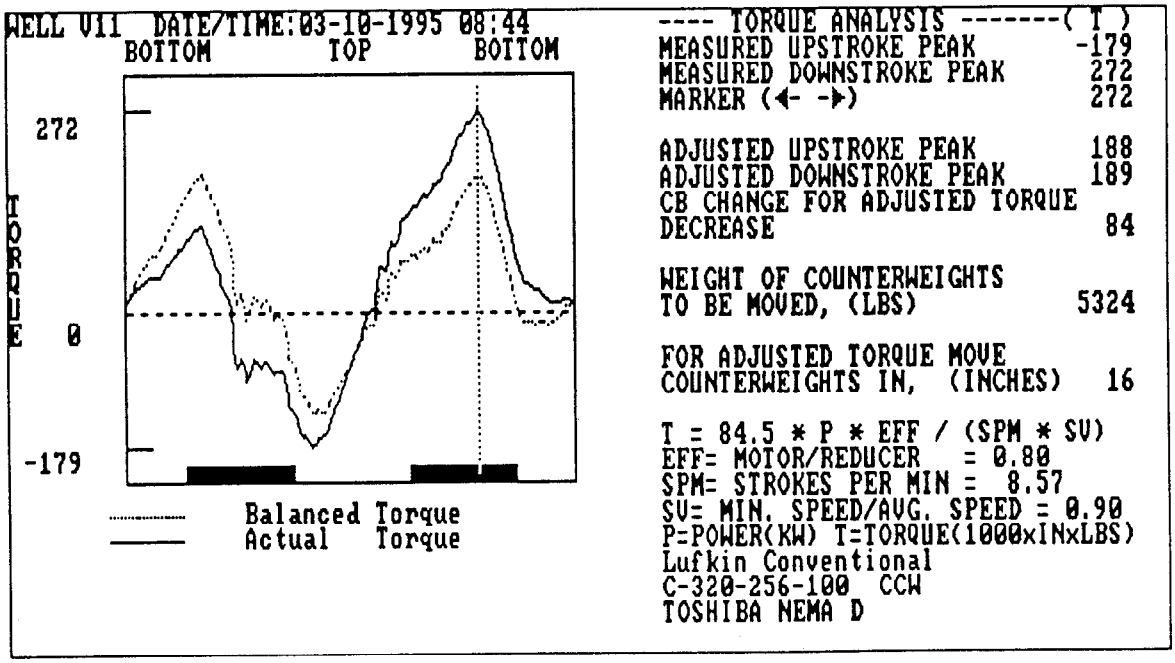

Figure 2 - Torque Analysis

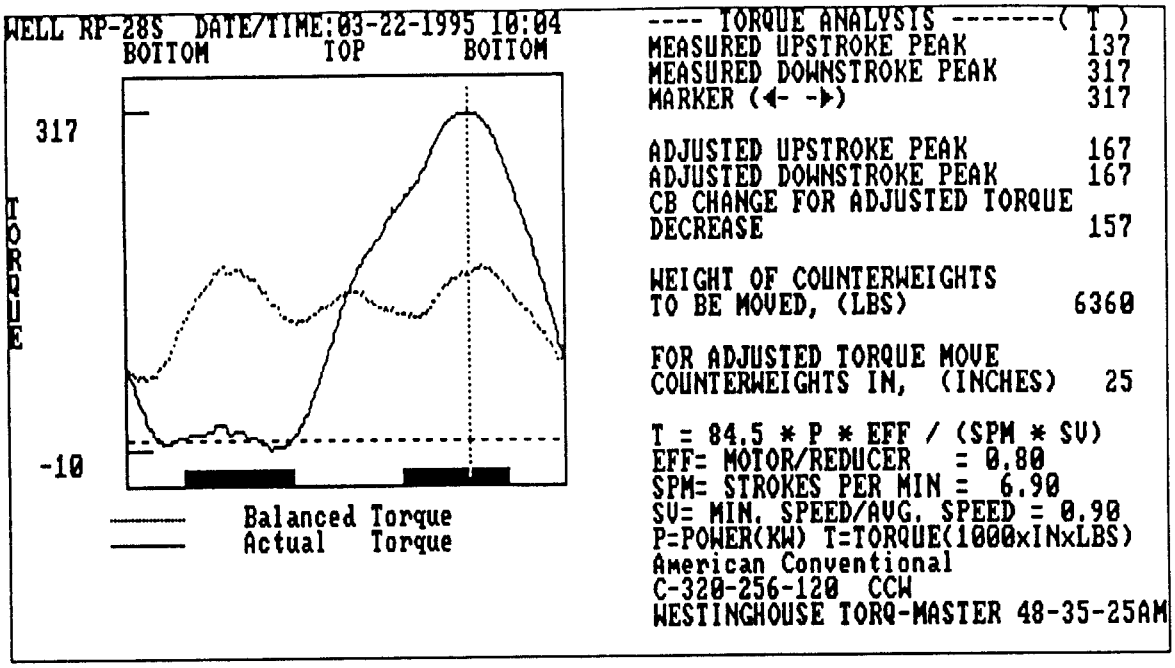

Figure 3 - Conventional Unit, Torque Analysis Shows Crank-Heavy Out of Balance

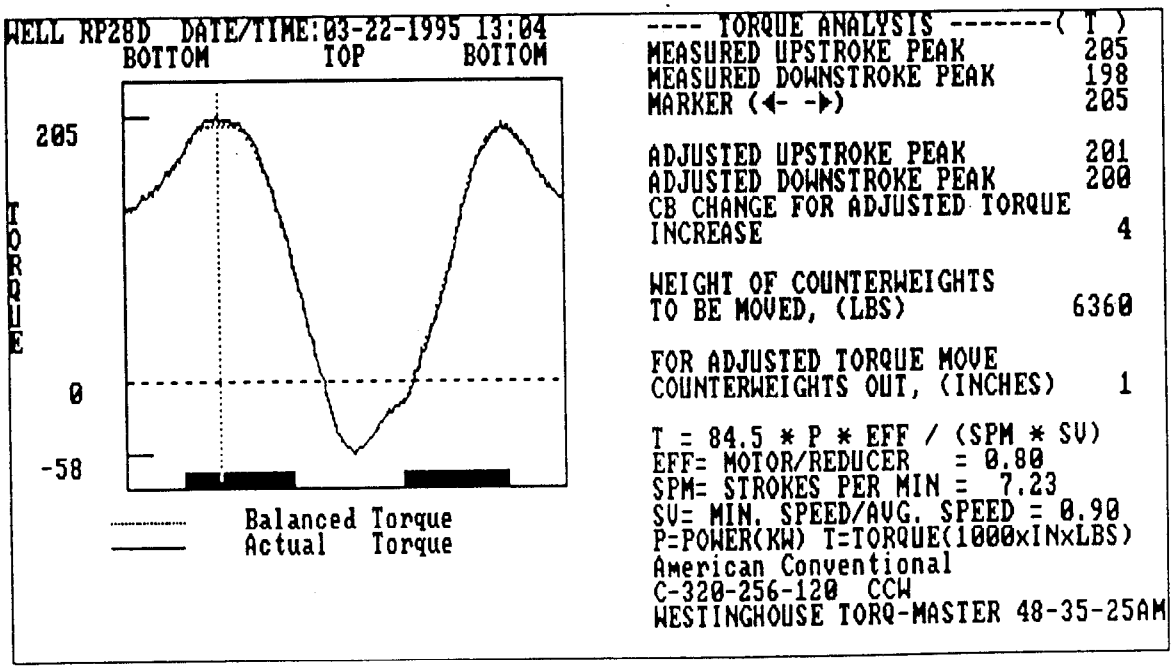

Figure 4 - Conventional Unit, Torque Analysis After Balancing

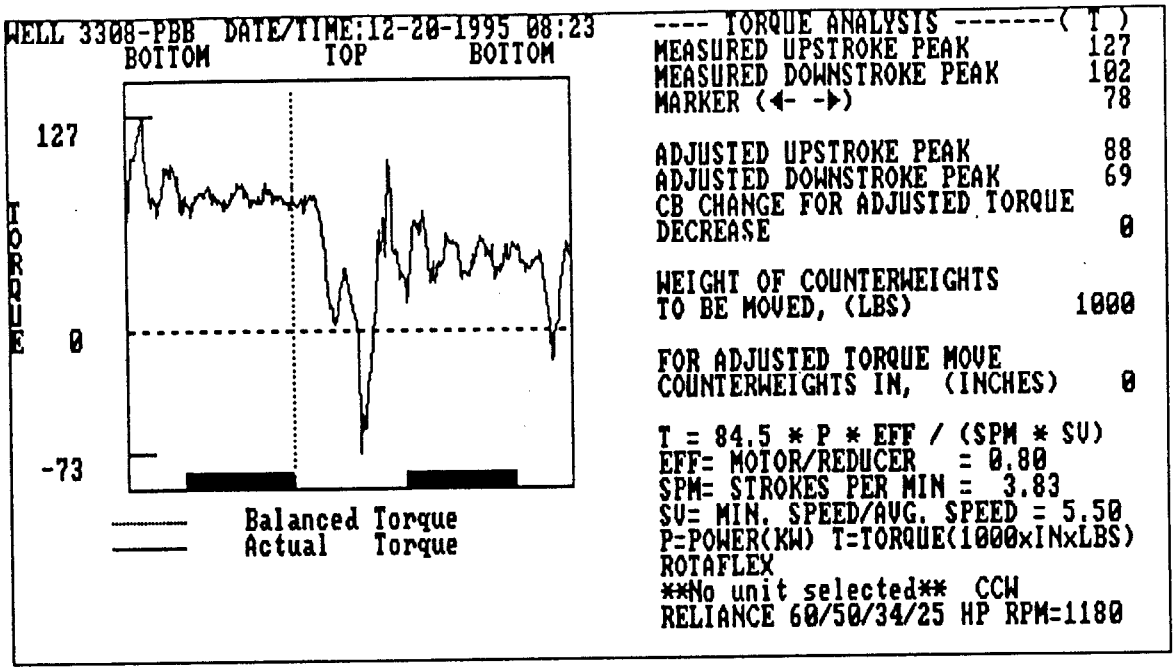

Figure 5 - Rotaflex Unit, Torque Analysis Shows Unit Underbalanced

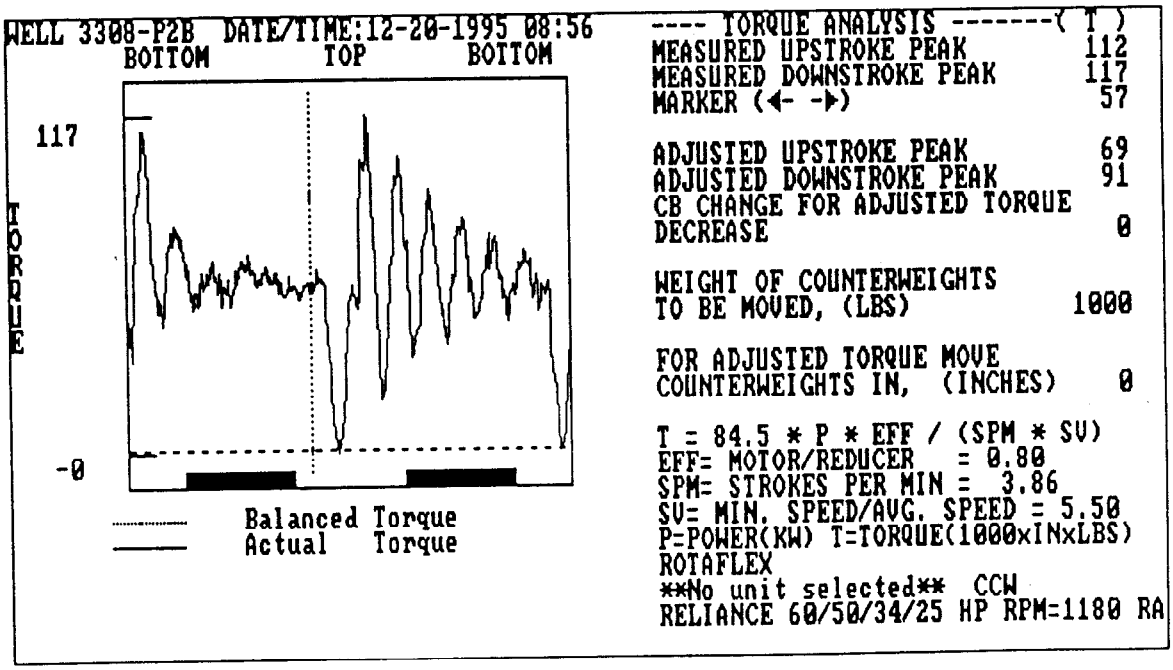

Figure 6 - Rotaflex Unit Torque Analysis After Balancing

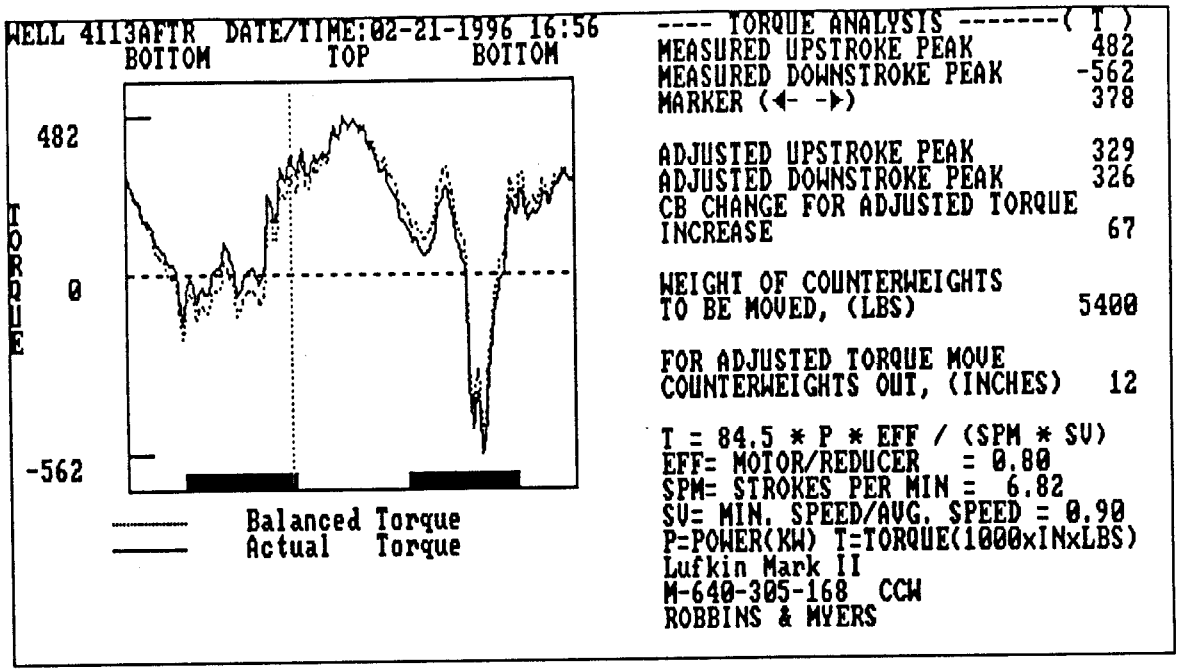

Figure 7 - Mark II Unit, Torque Data and Analysis

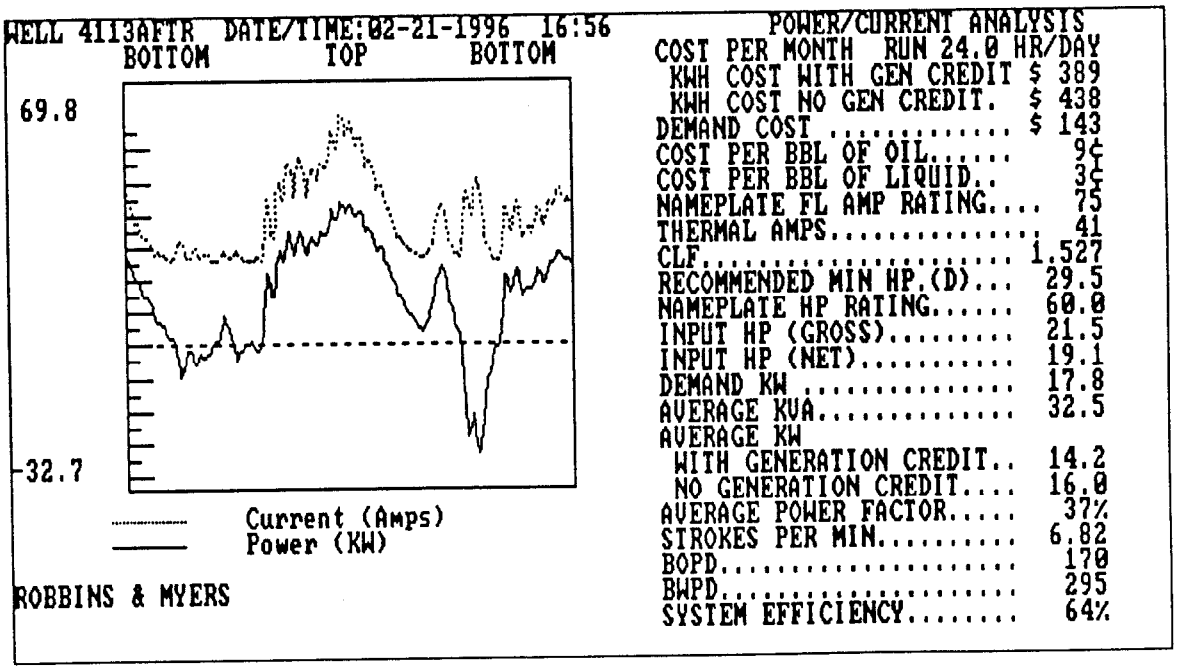

Figure 8 - Mark II Unit, Power Data and Analysis