Motor Design Slip Performance on Cyclic Loads

MARCUS O. DURHAM, SENIOR MEMBER, IEEE, CLARK R. LOCKERD, MEMBER, IEEE, AND JAMES F. LEA

Abstract—**Cyclic loads such as eccentric pumping units cause a varying torque on the driver. Determination of the most efficient induction motor for the load is discussed. Ultra-high-slip motors as well as NEMA design motors are evaluated. Comparisons of operating costs and investment are presented.**

Introduction

DETERMINATION of the most efficient electric motor driver for cyclic loading such as beam pumps has been a tedious problem. Most attempts at analyzing the problem have relied on anecdotal experience of one or two producing pumping units. Unfortunately, the conditions were not the same. Establishing a consistent test bed has not traditionally been possible [1].

The modeling of operating equipment has become much easier with the advent of computers and the ability to run many variations to a problem. Lea and Bowen have illustrate the efficacy of using models compared to actual field measurements on pumping units [2]. A comparison of the most cost-effective motor for pumping unit application will be determined using computer modeling for the changing torque load. Actual motor data curves will be used with the model.

Techniques for optimal sizing of motors have been previously identified by Durham and Lockerd [3], [4]. These procedures primarily consist of selecting a motor that will be operating at its peak cyclic efficiency. The cyclic efficiency is much different from the rated efficiency of the motor as shown by Durham and Lockerd [5]. The effect of using different motors to produce the same fluid production has been studied by Lea and Durham [6].

The economics of using the most cost-effective motor should be obvious. Electrical costs range from 20 to 25% of the direct operating cost for petroleum production [3]. When determining the best cost performance, it is necessary to evaluate both the initial investment and the operating cost. The paper will illustrate the possible trade-off between capital expenditure and operating cost.

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M. O. Durham is with THEWAY Corporation, and the University of Tulsa, P.O. Box 33124, Tulsa, OK 74153.

C. R. Lockerd is with OXY USA, P.O. Box 3908, Mail Stop 28 stb, Tulsa, OK 74102.

J. F. Lea is with AMOCO Production Research, P.O. Box 3385, Tulsa, OK 74102.

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Motor Design

The performance of a motor is influenced by the load that is connected to the shaft. Conversely, the cyclic load on the shaft will be influenced by the stiffness of the motor that is driving the load.

Motor rating curves are based on an assumption of a steady load over the normal operating range of the motor. For example, a pump or compressor would provide a reasonably constant load on the motor shaft. However, a punch press or a beam-pumping unit would provide a much different shaft load. The load could vary from no load to an extreme overload for a short period of time.

The cost of operating a motor is based on the amount of electrical power applied to the motor windings. The electrical energy is converted to heat losses and to mechanical power on the shaft:

$$\text{kW in} = (\text{hp out})(746)/\text{efficiency}.$$

However, the shaft horsepower changes with the torque demanded by the load. The speed of the shaft is also proportional to the horsepower:

$$\text{hp out} = (\text{torque})(\text{speed})/63\,000.$$

Therefore, if the torque oscillates during a normal operating cycle on the pumping unit, the horsepower and speed will vary. This makes it very difficult to determine an energy cost directly.

Manufacturers have developed alternative motor designs for constant loads and for cyclic loads. Cyclic loads tend to have very high torque requirements during part of the cycle. To provide the high torque, the motors generally have an accompanying high slip. Slip is the ratio of speed variation to the nominal speed of the motor:

$$\text{slip} = \frac{w \text{ synchronous} - w \text{ shaft}}{w \text{ synchronous}}.$$

The efficiency changes inversely with a change in speed. As the shaft speed slows, the slip increases. The direct efficiency of the motor will also decrease. However, there is a reduction in peaks during the cycle that may offset some of the loss in efficiency of the motors.

Custom designs have been developed in an attempt to

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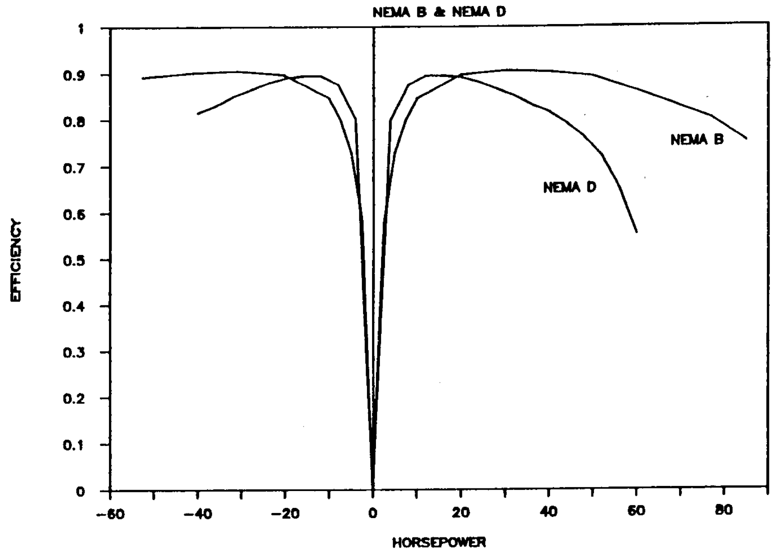

Fig. 1. Motor efficiency, steady load.

optimize the performance of motors on beam-pumping units. Most of these designs increase the torque output of the motor with an accompanying very high slip. Some of these motors have speed variations as high as 50%.

The benefits attributed to very high-slip motors are a reduction in peak torque on units and a reduction in peak polished rod loading. Limited empirical comparisons have been available based on observation of one or two wells. This restricted information has not provided a complete record of the effect of peak torques on the system efficiency.

Motors

The standard information available for motors includes the horsepower, current, speed, power factor, and efficiency at discrete points. Torque at strategic points is also available. The data points can be used to determine the speed variation and efficiency for a motor.

All these characteristics vary with the design of the motor. The National Electric Manufacturer's Association (NEMA) has developed performance criteria for standard motors. Ultra-high-slip motors are special-purpose machines that do not fit the standard specifications.

An illustration of the difference in the steady load efficiency for NEMA design motors are shown in Fig. 1. The NEMA B motor is designed for low starting torque applications while the NEMA D machine is intended for higher starting torque. The difference in the efficiency curves prompted our investigation of the effect of cyclic loading on the motor efficiency.

Torque Correlation

The pumping unit input horsepower is the power that must be output from the motor. An interesting observation is the pumping unit performance and power requirements will vary depending on the motor used. An almost infinite variety of load combinations can be developed using pumping unit configuration, stroke length, speed, horsepower, and fluid volume. Another constraint is that the motor slip should not significantly exceed the maximum slip recommended for the design, although the performance is sometimes better at extreme speed variations.

The effect of overloading equipment is a shortening of the life of the machine. The reduction in life is an exponential decay function.

Static torque curves for pumping units are available in API publications [7]. These curves represent the torque load on the unit at the instant it is starting. Since the curves do not include inertia, a complete analysis of operating performance is not available. Dynamic curves including inertia have been calculated by Nabla [8]. These curves provide the torque loading characteristics for a conventional pumping unit under running conditions.

The difference between gearbox torque and motor torque can be observed in Fig. 2. The motor torque was scaled to have the same peak as the gearbox torque. A smoothing of the torque load on the motor takes place. This results in less motor loading when the torque makes a negative transition. The significant effect is the motor actually regenerates less power. Part of the negative energy from the gearbox is absorbed in motor rotor and bull gear inertia as well as belt stretch.

The gearbox torque data and motor speed were available from the dynamic torque curves of the pumping unit. The motor speed data were correlated with the motor performance curve to obtain the motor torque curve for this loading. Duncan Butlin of User-Tek has done extensive work in this area and contributed information to correct the torque data.

Cyclic Efficiency

The horsepower required from the motor can be calculated from the dynamic torque curves. The speed of the shaft as

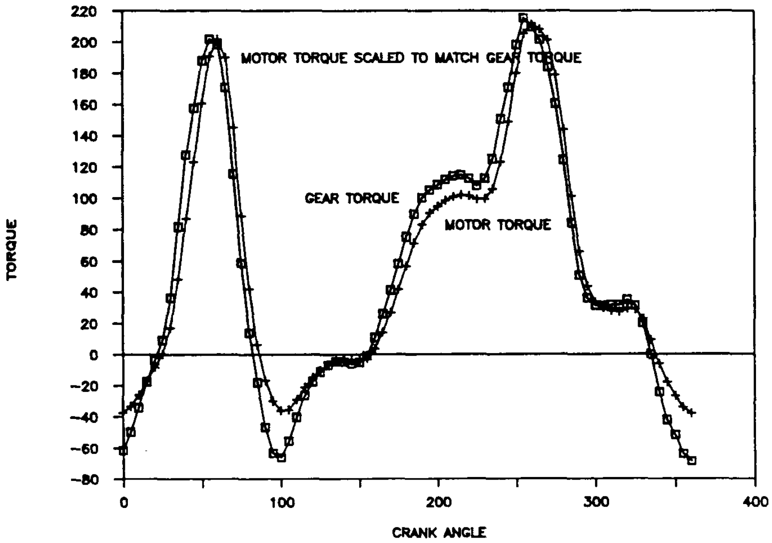

Fig. 2. *Gearbox and motor torque.*

well as the torque must be used to determine the motor horsepower.

The pumping unit torque curve characteristics were applied point by point to the motor steady-state performance curve. When the motor curve is invoked over one complete pumping unit torque cycle, the data represent only one average horsepower load on the motor.

The torque characteristic is considerably different with different speed variations. As the load changes on the motor, the torque characteristic must also change to correspond to the motor speed variations. The wide range of speed variations in ultra-high slip (UHS) motors require the consideration of this torque change. The torque characteristic change can be seen by comparing Fig. 3 with Fig. 2.

The pumping unit torque was determined at a discrete crank angle. The torque was applied to the motor curve to determine the speed and efficiency. The speed and torque were used to determine motor output horsepower. The horsepower and efficiency were used to determine losses.

The efficiency at discrete points on the scaled horsepower curve is taken from the motor steady load curve. The instantaneous losses are then calculated using brake horsepower (BHP):

$$\text{losses} = (\text{BHP}/\text{eff motor}) - \text{BHP}.$$

The horsepower from all the discrete points can be added to determine an average horsepower for the specified load conditions. Similarly, the losses at all the digitized points can be added to obtain the average losses. The overall motor efficiency under cyclical load can then be calculated:

$$\text{eff cyc} = \text{actual hp}/(\text{actual hp} + \text{actual losses}).$$

This representation is the effective load on the motor for one torque characteristic. The shape of the torque curve dictates the speed variation of the motor. A different shape or magnitude torque characteristic will affect the motor loading. The analysis performed represents only one average torque loading for a particular torque characteristic using a given motor.

By scaling the torque curve without changing the shape, a suite of individual cyclic loads can be obtained. Using these loads, the performance of the motor over a range of cyclic operating loads can be plotted.

A variety of motors were applied to the cyclic load. Fig. 4 is a plot of the efficiency over the operating horsepower range of the motors. The curves were discontinued when the motor stalled.

Several fascinating observations are available. First, the speed variation is greater when a smaller size motor is used. The slip continues to decrease as larger and larger motors are applied. This reflects that larger motors provide "stiffer" power. The base load is the same for all the installations. Less power is available from smaller motors; therefore, the speed must decrease. A decrease in speed represents an increase in slip.

Furthermore, minimum power occurs using an intermediate size motor. The costs increase if a smaller or larger motor is used. This correlates with analysis obtained in previous papers by Durham and Lockerd [3], [4]. Low horsepower motors are operating on the top end of the efficiency curve where efficiency begins to drop. Similarly, large horsepower motors are operating on the low end of the curve where no-load losses have an adverse effect on efficiency.

Motor Performance

A comparison of the performance of each design motor illustrates the advantages and disadvantages of the design.

NEMA D

The NEMA D motor has the widest operating range. A 25-hp motor can operate up to a 24-hp average load. Its best efficiency occurs near a 10-hp average cyclic load. Operating at 10 hp permits a large increase in load for unbalanced pumping unit operation. The NEMA D provides the widest swing in load performance. The motor rating should be 2.5 times the cyclic loading for best efficiency.

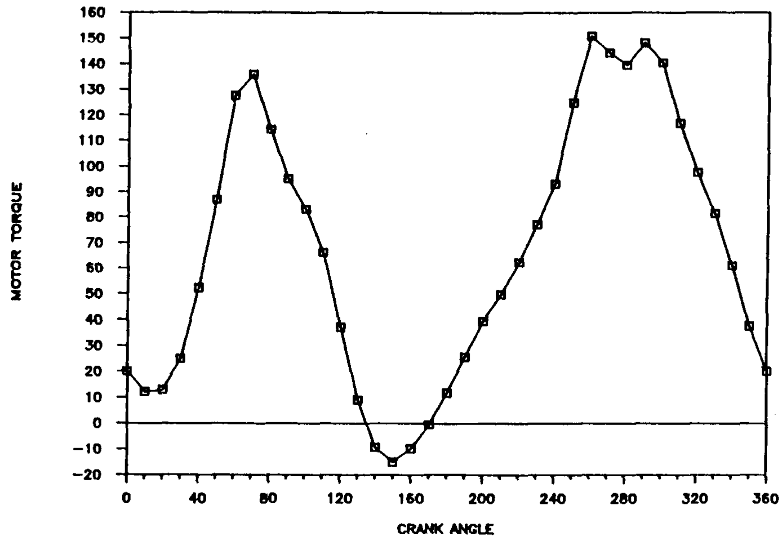

Fig. 3. Motor torque at 43% speed variation.

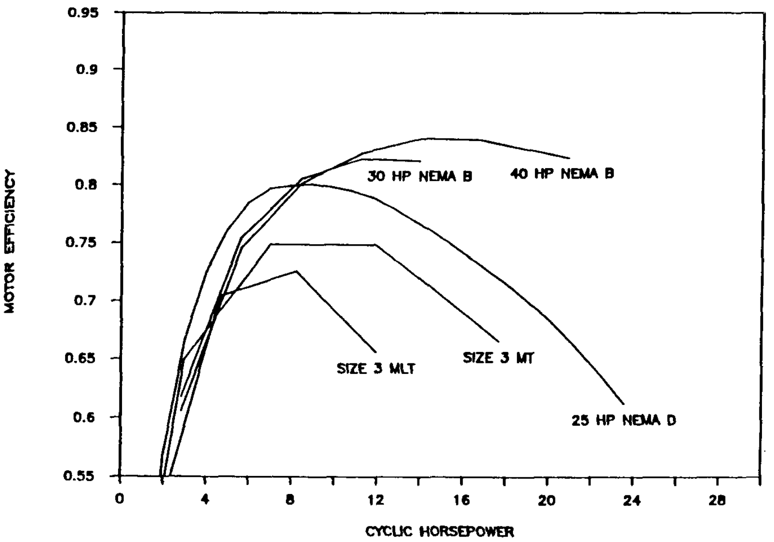

Fig. 4. Motor efficiency, cyclic load.

Ultra-High Slip Performance

Each frame size motor has multiple ratings depending on how the windings are connected. In the high-torque mode the motor has maximum horsepower. The minimum horsepower occurs in the low-torque mode.

Because of the four torque modes available for each ultra-high slip motor, multiple operating data points are available. In effect, each motor must be analyzed as four independent motors. In the high torque mode, the motor is very similar to a NEMA D design.

Interestingly, the ultra-high slip motor efficiency on a cyclic load decreases as the torque rating of the motor decreases. In the medium torque mode, the UHS motor is approximately 4% less efficient than the NEMA D.

Another observation is this particular size motor in its lower torque modes does not have as wide a performance range as the NEMA D motor. A size 4 UHS motor would compare more favorably to the 25-hp NEMA D.

Low-Slip Motors

Conventional NEMA B design motors are rated for low-slip and low-torque applications. However, they may be applied to cyclic loads. The major consideration is that the motor will be somewhat larger than a high-slip NEMA D or an ultra-high-slip motor.

Because of the ready availability of these motors and their low price, they must be considered as an alternative to their higher slip counterparts. Furthermore, the equipment has been used for years on single-phase pumping unit installations where NEMA B is the only equipment available.

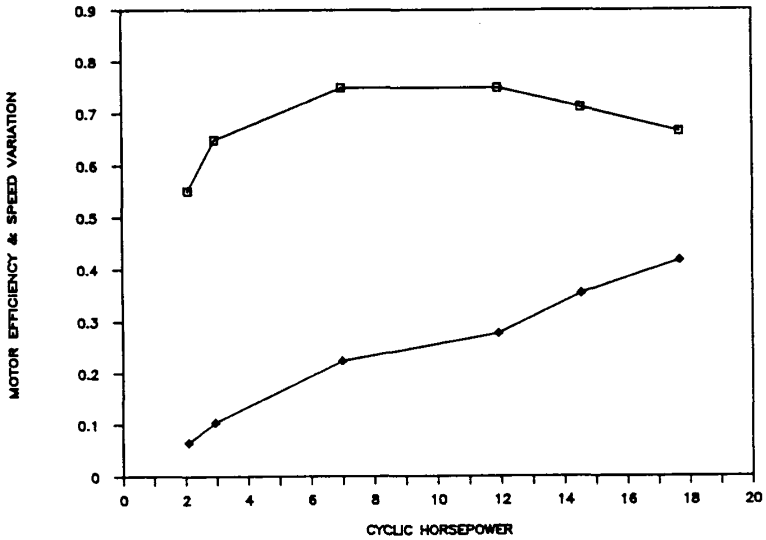

Fig. 5. Motor speed variation.

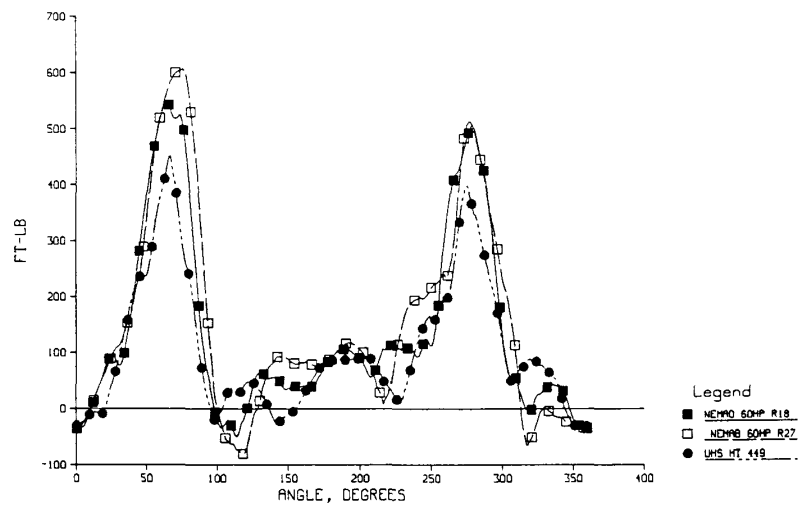

Fig. 6. Motor torque at 8.1% speed variation.

The NEMA B motors are significantly more efficient than the higher slip units. They are approximately 6% more efficient than the NEMA D and 10% more efficient than the medium-torque ultra-high-slip motors.

However, the motor reaches peak efficiency near its maximum load. This restricts the amount of horsepower load that can increase during unbalanced operations. Operation at the peak leaves little room for the periodic unbalance associated with erratic well conditions. The motor rating should be four times the cyclic loading for best efficiency and to allow a reasonable range of horsepower for unbalanced operations.

Speed Variation

The motor and pumping unit both go through a wide variation in speed. The motor speed change on the cyclic load is shown in Fig. 5.

The importance of motor speed change is its impact on the shape of the torque curve. Fig. 6 provides a torque-versus-angle curve for three different design motors. The motors are at the same percent speed variation.

The magnitude of the curves is not significant because they are designed for different average cyclic loads. However, the shape of the curves is significant. Using the same scaling, the NEMA curves provide very similar shapes for the torque curves. The ultra-high slip is also very similar, but it has less regenerative power.

Motor Starting

The selection of a correctly sized motor has long been a tedious process that has elicited many variations. Durham and Lockerd presented a method in an earlier work [3]. An abbreviated procedure is presented.

A critical feature of the motor must be its ability to start the pumping unit from a stationary position. The torque-position curves for pumping units shown in [7] are for static conditions. Scaled values for peak torque and average running torque can be taken from these curves. The peak-to-average torque (PAT) ratio can be used to select the size motor required for starting.

Motor performance is rated by the ratio of the breakdown-to-rated torque (BRT). The breakdown torque is the maximum torque the motor can deliver without stalling.

Average horsepower equals the torque times the speed. This relationship combined with the two factors can be used to determine the starting capability of a motor on a pumping unit. The horsepower required for the motor to start (MHP) is based on the average running horsepower required by the pumping unit shaft (SHP):

$$\text{MHP} = \text{SHP}^*(\text{PAT ratio})/(\text{BRT ratio}).$$

The starting torque (ST) ratio is the ratio of the PAT to BRT:

$$\text{ST ratio} = \text{PAT ratio}/\text{BRT ratio}.$$

The PAT ratio for API units has been previously determined [3]:

unconventional	2.53
conventional	5.66.

The BRT for NEMA motors is also listed [1]:

NEMA B	1.75
NEMA D	2.75.

Consider the performance of the NEMA D motor. On an unconventional unit the starting torque ratio is less than one $(2.53/2.7 = 0.94)$. Therefore, a motor that will run the unit will start the unit. On a conventional unit, the ratio is greater than one $(5.66/2.7 = 2.1)$. Hence a motor that will start the unit will run the load. However, the converse is not necessarily true. The minimum size motor that will run the unit will not start from a static position.

Comparisons

The cost of operation of the NEMA D, UHS, and the NEMA B motors is not significantly different on average. However, by careful selection of equipment, substantial savings can be obtained. These savings can only be obtained by detailed comparison between several motors applied to the exact operating condition of the well.

The comparisons between motors require a quite sophisticated computer model for each installation. The most efficient system can be designed only when an *accurate usable* computer model is available. Unfortunately, many of the computer program systems presently used are not appropriate in general. The most effective programs would allow "what if" options so a variety of parameters could be compared, such as operating cost and peak torque.

A rule-of-thumb approach is not acceptable. With misapplication, it is easy to cause a substantial waste of electricity. This is particularly true of ultra-high-slip motors. Moreover, the proper operation of the equipment under balanced conditions has an even larger overall effect than the initial selection of the motor.

From the data shown, in general the NEMA B motor has the lowest electrical cost. Next in cost is the NEMA D, then the ultra-high slip. This reduction in electrical energy costs reflects the increase in efficiency of the motors.

However, as with every engineering problem, there is a trade-off. The penalty for increased motor efficiency is a stiffer motor. A stiffer motor in turn increases the peak loading on the pumping unit and rods.

An interesting observation is the shape of the efficiency curve for the various motors. The curve is almost flat for the NEMA B but varies widely for the other machines. Again this reflects the stiffness of the motor. Furthermore, the motor cannot be operated very far from its rated horsepower.

A final consideration is the investment cost in the motors. Using NEMA D as a reference value of 1.0, the NEMA B costs about 0.75, while the UHS 447 costs about 2.1 and the UHS 449 costs about 2.7.

The ultra-high-slip motor is a special-purpose tool that requires a significant investment and careful sizing. Nevertheless, if the equipment is appropriately sized, the operating cost can be minimized. Furthermore, the equipment can reduce the peak torque on the system.

Summary

Several significant observations can be made from the study of various motors applied to cyclic loads.

1) Any type design motor will work on a pumping unit.

2) The motor must be carefully sized to provide minimum operating cost.

3) The least expensive operating cost and the least investment comes from the motors with the least slip.

4) The lower slip motors cause an increase in peak torque on the unit.

5) An accurate computer model with an easy-to-use program that allows "what if" options is highly desirable.

Recommendation

We have presented one method of determining the most efficient motor for a cyclic operation. Most users do not have the electrical background and resources to perform this investigation of every installation. The industry should consider developing a standard method of rating and testing motor performance as applied to a pumping unit load.

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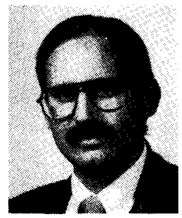
Marcus O. Durham (S'64–M'76–SM'82) received the B.S. degree in electrical engineering from Louisiana Tech University, Ruston, the M.S. degree in engineering systems from the University of Tulsa, Tulsa, OK, and the Ph.D. degree in electrical engineering from Oklahoma State University, Stillwater.

He is the principal of THEWAY Corp., P.O. Box 33124, Tulsa, OK, an engineering, management, and operations group conducting training, computer development, and design of facilities and electrical installations. He is also an Associate Professor at The University of Tulsa, specializing in microcomputer applications and electrical/ mechanical energy systems.

He has published numerous papers, articles, and manuals and conducted training in such diverse areas as submersible pumps, beam pumps, failure analysis, power generation, corrosion and cathodic protection, facilities design, oilfield operations, safety, grounding, electrical power design and management, and microcomputer applications.

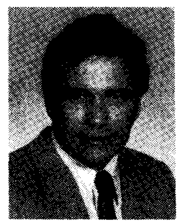
Dr. Durham is a Registered Professional Engineer in the States of Oklahoma and Louisiana, a State Licensed Electrical Contractor and an FCC-licensed radiotelephone engineer. He has served on and been Chairman of many committees and standards groups within the IEEE, SPE, and API. He is a member of the Society of Petroleum Engineers, Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu.



Clark R. Lockerd (S'72–M'78) received the B.S. degree in electrical engineering from the University of Wyoming, Laramie.

He was an Electronic Design Engineer for Motorola GED. He is now the Electrical Engineering Supervisor for OXY USA, Inc., Tulsa, OK. He is responsible for all electrical engineering projects in oil and gas production. This includes power distribution, motors, controls and computer automation systems. He has published many papers on beam pumping, electrical design and programmable logic controllers used as RTU's in SCADA systems.

Mr. Lockerd is a member of the Society of Petroleum Engineers. He is Past Chairman of the Production Subcommittee of PCIC/IAS.



James F. Lea received the B.S. and M.S. degrees from University of Arkansas, Fayetteville, and the Ph.D. degree from Southern Methodist University, Dallas, TX, all in mechanical engineering.

He was worked with Pratt & Whitney, United Florida, Sun Oil Company, and the University of Arkansas. He is now a Special Research Associate for Amoco Production Research Center, Tulsa, Oklahoma. This job involves the evaluation of production operations techniques with special emphasis on artificial lift operations. He has published numerous papers and articles covering topics such as submersible pumps, beam pumps, gas lift, production optimization, and fluid mechanics.

Dr. Lea is a Registered Professional Engineer in Oklahoma. He is a member of the Society of Petroleum Engineers and American Society of Mechanical Engineers. He has served on many committees and standards groups within the SPE and API.