Facts and Fiction of HVAC Motor Measuring for Energy Savings

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The impetus for the empirically derived data presented in this paper was a program established by the State of Arizona to replace all the existing HVAC motors in the majority of State-owned buildings. After obtaining questionable data from the initial existing motor field measurements[1], it was decided that some further study and testing was needed. By dynamometer testing aging motors from the field and new energy efficient motors, some startling conclusions were realized.

One of the most common methods for determining motor loads in the field, the slip method (Bonneville Power Administration, 1990 and Lobodovsky, 1994), is highly inaccurate and cannot be used to reliably determine the load on the motor. Field measurements reconciled with dynamometer testing[2] reveals that the slip method can be over 40% in error (see Table 2).

Replacing an existing motor with an energy efficient motor may actually use more energy due to the effects of RPM differences. Energy efficient motors generally run faster than standard motors because of the inherent lower internal losses. However, because the power required by a centrifugal load induction motor varies as the cube of the speed (Karasik, 1976 and Spitzer, 1987), the savings due to the higher efficiency may be completely offset by the increased power requirement due to the faster speed.

Some of the conventional practices for projecting and determining energy savings from HVAC system energy efficient motor retrofits are misleading. Using the slip method for calculating motor load and not accounting for the speed difference between the existing motor and new motor are two examples.

Introduction

The impetus for the empirically derived data presented in this paper was a program established by the State of Arizona to replace all the existing HVAC motors in the majority of State-owned buildings. All motors from 5 HP up were selected as candidates for retrofit. The largest motor was 125 HP. Upon taking the initial field measurements, it was realized that the data being gathered were inconsistent and unreliable.

Since determining the load on the existing motor was essential to projecting the energy savings and selecting the energy efficient motor replacement, a thorough analysis of the ubiquitous slip method was needed.

As the program progressed, other nuances were discovered and researched to determine their effects on savings. The most important discovery was the effect on energy savings of the inherent higher full load operating speeds of the new energy efficient motors.

Methodology

It was determined that few published motor replacement strategies included all the necessary ingredients for projecting and determining the actual energy savings—or even if there were savings. Nearly all savings calculations were based on assumptions that, though they appeared to make sense, had not been field verified.

To add to the confusion, sometimes assumptions that were based on a particular motor application were then extrapolated to other motors *(Engineered Systems, 1993).* This is the “identical system” or “identical building” syndrome. Once field measurements are begun, it is quickly realized that finding two motors with identical operating characteristics is purely coincidental. Projecting operating characteristics such as load, amps, or rpm from one motor to several others can result in substantial errors when calculating anticipated energy savings.

It was decided that the strategy for this program should be started from scratch and an experimental approach was developed. First, specific motors were selected from the existing installations to be dynamometer tested and compared to the operation of new energy efficient motors subjected to the same test conditions. Then the conclusions from the tests were used in the field to measure and select energy efficient motor replacements.

There were several tools required. An energy analyzer[3] was used to measure true rms volts and amps, kW, power factor, and other pertinent electrical characteristics. A non-contact strobe tachometer was used for measuring motor rpm. An infrared thermometer was used for motor temperature measurements. In addition, a standard clamp-on amp meter and common hand tools were used.

Initial Test Results

The initial test results demonstrated that certain common practices were not acceptable. Other well-understood practices that have significant effects on energy use are not being routinely applied. The most important of these is the effect of motor speed on power requirements.

Motor Speed and Power

The Slip Method. The results obtained early in the program regarding motor load were inconsistent. The true rms amps showed some motors full or nearly full loaded and the slip method showed the load something much less–or more–than the amps. Since there was a relatively high confidence level in the full load amps, it was decided to start examining the slip method procedure.

Traditionally, the slip method is used to calculate the load on the motor by taking the difference between the synchronous speed and the measured speed (as measured with a strobe tachometer, in this case), then dividing that by the synchronous speed minus the full load nameplate speed. The formula is as follows:

$$\frac{\textit{sync rpm} - \textit{measured rpm}}{\textit{sync rpm} - \textit{nameplate f. l. rpm}} = \textit{load}$$

As an example, one motor measured was a 20 HP, 1800 rpm synchronous speed motor with a nameplate full load rpm of 1750 and a measured operating rpm of 1780. Using Equation (l), the load computes to a 40% load. Since the amp measurement was much closer to the nameplate full load amps, there was reason to investigate further. It was important to understand this because a 40% loaded motor is a candidate for downsizing, whereas a motor loaded to more than 50% is not.

There are several factors influencing these measurements that can cause the actual load to be significantly different.

The first is that the nameplate data can vary as much as 5 rpm[4,5]. Five rpm is a fraction of a percent of the full load rpm and is often regarded as insignificant. However, the slip method is calculated on the *difference between the full load nameplate rpm and the synchronous speed;* in this case only 30 rpm. Now the 5 rpm causes a 16% disparity when calculating the load using the slip method.

The second issue is that of motor temperature. Both dynamometer and field testing confirmed that as the motor temperature increases, the full load rpm decreases[4,5]. It was typical to find a 4 rpm difference in the full load speed for a cold (room temperature) motor and a warm motor. Again, though 4 rpm is insignificant in comparison to the full load speed, it is over 13% of the difference between the full load nameplate speed and synchronous speed (see Table 1).

Table 1. Measured Motor Speed vs. Temperature

Motor hp	Amp Load	Name-plate rpm	Cold rpm	Hot rpm	Diff. rpm
15	100%	1770	1777	1774	3
15	81%	1760	1766	1762	4
20	109%	1740	1750	1746	4

The third issue is that of operator error. Many tachometers are difficult to read the exact rpm at any one instant. The type of tachometer used in this program was very accurate, but due to this, it was also quite sensitive. It was often necessary to take several minutes to get a reliable reading. Over the course of many readings by severs{ operators, it was found that rpm readings could vary by 2 rpm.

The fourth issue is the effect of operating voltage on the speed. The slip of an induction motor varies inversely as the square of the motor voltage ratio (Stebbins, 1993). In this program, it was found that the voltage was 15 to 30 volts more than the nameplate voltage rating. Though this has a relatively small effect compared to some of the other issues, it can compound the inaccuracy of using the slip method to determine motor load.

The last issue discussed here is the effect of motor rewinding on the operating characteristics. Though there are standard practices for motor rewinding (EASA, 1992) and the effect of rewinding on efficiency can be quantified (Montgomery, 1989), it is difficult to determine if the practices are being followed and it is impractical to try to determine the rewind efficiency in most cases. Further, it is difficult to determine in the field whether a motor has been rewound or not. It is important to note that rewinding motors can have an impact on the efficiency.

The slip method for determining motor load in the field is not recommended.

Amp/kW Load. Since the slip method is not recommended for determining motor load, there must be a reasonable way to approximate motor load in order to facilitate the energy savings calculations and to determine when to downsize. The kW load and amp are two possible methods.

Naturally, when the kW can be measured directly, this can be an accurate way to determine motor load. By dividing the measured kW by the calculated kW (nameplate HP x 0.746 x the inverse of the efficiency), the load can be estimated quite closely. The accuracy, however, depends largely on the estimate of the existing motor efficiency.

Figure 1 shows that the amperage of a motor is approximately linear down to about 50% load[b]. This means that the measured true rms amps divided by the nameplate full load amps should be a reasonably accurate way to determine load above 50%. Below 50% load, the amp curve becomes increasingly non-linear and, therefore, not a good indicator of load.

In this program, it was found that the vast majority of HVAC motors are generally about 70% to 75% loaded. It was also found that rarely was a HVAC motor less than 50% loaded.

Though not as accurate as some other methods requiring more work (Lobodovsky, 1994), like disconnecting the motor from the load, for example, it was discovered that the amp load was arguably the best method overall for determining motor load in the field. Table 2 shows some pertinent field and nameplate data for a sample of existing motors and, for comparison, Table 3 shows some pertinent field and nameplate data for the new motors which replaced those in Table 2.

As can be seen from Table 2, the mean amp load and mean kW load for the group were only 7% apart, while the slip load and kW load were 19% apart. The standard deviation for the amp load was only 13% whereas the standard deviation for the slip load was 32%, indicating further that the amp load is a more reliable method for determining motor load.

Important note: actual motor efficiency can be measured only on a dynamometer, it cannot be measured in the

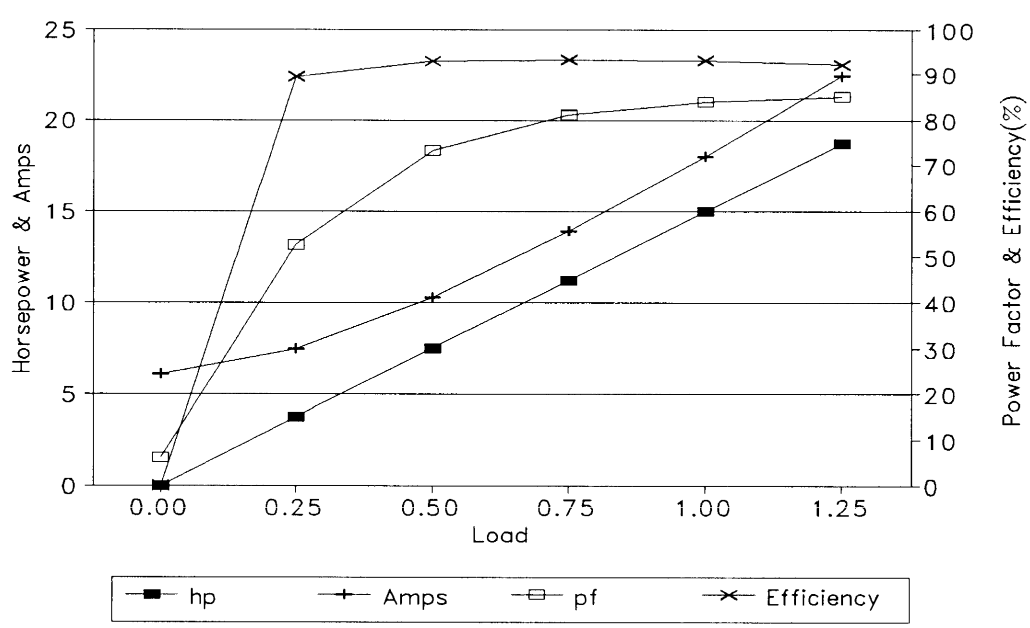

Figure 1. Factory Test Data for 15 HP Motor

Table 2. Characteristics of Existing Motors Measured in the Field

Motor Number	Motor hp	Old Motor rpm	Old Motor Nominal Efficiency	Name-plate Amps	Meas-ured Amps	Meas-ured rpm	Meas-ured p.f.	Amp Load %	Slip Load %	kW Load %	Old Motor kW
29	7.5	1755	84.2%	10.5	9.9	1768	0.72	94%	71%	90%	6.0
28	7.5	1755	84.2%	10.5	9.6	1766	0.73	91%	76%	90%	6.0
27	7.5	1760	84.2%	10.5	13.0	1743	0.80	124%	143%	131%	8.7
62	10	1755	85.0%	13.5	14.0	1765	0.78	104%	78%	103%	9.0
92	15	1750	85.3%	20.8	15.7	1786	0.60	75%	28%	60%	7.9
42	15	1750	85.3%	18.7	17.1	1779	0.71	91%	42%	78%	10.2
34	15	1750	85.3%	20.8	17.8	1780	0.63	86%	40%	72%	9.4
96	15	1750	85.3%	18.7	17.0	1780	0.72	91%	40%	76%	10.0
97	15	1750	85.3%	18.7	14.5	1784	0.66	78%	32%	61%	8.0
94	15	1750	85.3%	18.7	16.0	1782	0.73	86%	36%	74%	9.7
47	15	1750	85.3%	20.0	16.3	1763	0.78	82%	74%	81%	10.6
93	15	1760	85.3%	21.0	17.0	1758	0.65	81%	105%	69%	9.0
64	20	1755	87.3%	25.6	19.1	1777	0.81	75%	51%	75%	12.7
32	40	1770	89.8%	50.0	37.8	1783	0.73	76%	57%	70%	23.2
						Mean	0.72	88%	62%	81%	10.03
						StdDev	0.06	13%	32%	19%	4.18
						Max	0.81	124%	143%	131%	23.20
						Min	0.60	75%	28%	60%	6.00

Table 3. Characteristics of New Energy Efficient Motors Measured in the Field

Motor Number	Motor hp	New Motor rpm	New Motor Nominal Efficiency	Name-plate Amps	Meas-ured Amps	Meas-ured rpm	Meas-ured p.f.	Amp Load %	Slip Load %	kW Load %	New Motor kW
29	7.5	1755	91.7%	9.45	7.7		0.83	81%		88%	5.4
28	7.5	1755	91.7%	9.45	7.5		0.83	79%		86%	5.3
27	7.5	1755	91.7%	9.45	10.6		0.89	112%		128%	7.8
62	10	1755	91.7%	12.7	11.8	1767	0.82	93%	73%	98%	8.0
92	15	1770	93.0%	19.0	12.4		0.70	65%		60%	7.2
42	15	1770	93.0%	19.0	15.8	1782	0.78	83%	60%	85%	10.2
34	15	1770	93.0%	19.0	14.6	1786	0.76	77%	47%	76%	9.2
96	15	1770	93.0%	19.0	14.9	1784	0.78	78%	53%	78%	9.4
97	15	1770	93.0%	19.0	12.5	1787	0.71	66%	43%	61%	7.3
94	15	1770	93.0%	19.0	14.1	1784	0.76	74%	53%	73%	8.8
47	15	1770	93.0%	19.0	15.4	1784	0.75	81%	53%	82%	9.9
93	15	1770	93.0%	19.0	13.2	1786	0.75	69%	47%	68%	8.2
64	20	1755	91.7%	24.0	16.8	1775	0.86	70%	56%	73%	12.0
32	40	1775	94.5%	47.0	31.8	1785	0.84	68%	60%	88%	22.2
						Mean	0.79	78%	55%	82%	9.35
						StdDev	0.06	12%	9%	17%	4.11
						Max	0.89	112%	73%	128%	22.20
						Min	0.70	65%	43%	60%	5.25

field, therefore a reasonable estimate must be made. Though there is a method for calculating the efficiency of an installed motor (BPA, 1990), it depends largely on the accuracy of the load as calculated by the slip method. Since small errors in load calculation cause large errors in the efficiency calculation, neither the slip load nor the amp load is acceptable. For this program, the efficiency was assumed to be the average standard efficiency for the HP size in question minus 1% for motors in the 5 HP to 25 HP range and the average standard efficiency minus 1/2% for 30 HP motors and larger.

Speed and Efficiency. Energy efficient motors are more efficient because they have lower internal losses. This causes them to run faster. Unfortunately, the faster speed causes the power requirement to increase.

To fully understand this, it is beneficial to discuss the applications of variable speed motor drives (VSDs). The energy saving potential of VSDs is well understood and the application of VSDs is quite common. What causes the significant energy savings from VSDs applied to centrifugal loads is one of the centrifugal pump and fan "affinity laws" which states that the power requirement varies as the cube of the speed (Karasik, 1976 and Spitzer, 1987). For example, a motor operating at 90% of full load speed requires only 73% of the full load power ($0.9^3 = 0.729$). The "cube law", as it sometimes called, is:

$$(P_2/P_1) = (N_2/N_1)^3$$

Where P_1 and N_1 are the power and speed of the existing motor, respectively, and P_2 and N_2 are the power and speed of the new motor.

Unfortunately, the law also applies when the speed increases. In the case of replacing an existing standard efficiency motor with a new energy efficient motor (higher operating rpm), it is necessary to take into account the negative impact of the greater speed. For example, an existing motor with a full load speed of 1750 rpm may be replaced with an energy efficient motor with a full load speed of 1765 rpm (a very likely scenario). In this case, the increased speed would cause an increase in horsepower, or similarly, an apparent decrease in efficiency. The net effect on power would be:

$$(1765/1750)^3 = 1.026 \textit{ or } +2.6\%$$

In other words, the new motor requires 2.6% more power when compared to the existing motor. This increase in power has an apparent effect of reducing the efficiency as follows:

$$\Delta EFF = EFF_{new}\ [1-(RPM_{ex}/RPM_{new})^3]$$

For example, using the speed assumptions above, if the existing motor was a 20 HP, 89.5% efficient motor, and the new motor was a 20 HP, 93% efficient motor, the new motor would effectively be only about 1% more efficient. To account for the increased speed, 2.4% must be subtracted from the 93% to result in an apparent efficiency (as compared to the existing motor) of 90.6%. Of course, the efficiency of the new motor is not really reduced, but the increase in operating speed over the old motor must be accounted for (see Table 4).

Table 4. Effects of Motor RPM on Power*

Old Motor rpm	New Motor rpm	rpm Increase	Power Increase	Apparent** Efficiency Decrease
1750	1755	5	0.9%	-0.8%
1750	1760	10	1.7%	-1.6%
1750	1765	15	2.6%	-2.4%
1750	1770	20	3.5%	-3.1%
1750	1775	25	4.3%	-3.8%
1750	1780	30	5.2%	-4.6%

* For motor with centrifugal load. New motor nameplate efficiency of 93%.

** This is the apparent effect on the new motor efficiency taking into account the difference in motor speeds.

Using the data from the sample of 14 motors presented in Tables 2 and 3, it can be seen that the actual kW reduction was an average of 680 watts for each motor (the kW mean from Table 3 subtracted from the Table 2 kW mean). The projected kW reduction based on the amp load *accounting for the speed,* is 691 watts—1.6% higher than the measured savings. However, when the kW reduction is projected based on the amp load *without accounting for the speed,* the projection is *895* watts—nearly 32% higher than the actual savings.

Another way of compensating for the increase in speed is to re-sheave the fans and trim impellers on pumps. Resheaving the fans may be cost-effective in some cases and is reversible so it can be considered. Impeller trimming on pumps is not reversible and was determined not cost-effective in most cases. If considered, the cost of these options must be included in the cost analysis.

Due to the disparity of field measurements, differences in actual vs. nameplate data, and the fact that small changes in some numbers cause large differences in the resultant calculations, it is recommended that energy savings be projected to groups of motors, not individual motors.

Catalog Data. Great caution must be exercised when basing calculations on manufacturer's published data. It was discovered that the nameplate data on the new motors rarely matched the catalog data, especially in the case of the full load rpm.

In this motor replacement program, each replacement motor was selected on the basis of its nominal efficiency and full load rpm as published in the manufacturer's catalog. However, when the motor's nameplate was inspected, the full load rpm was nearly always more than the manufacturer's published data. In the most extreme case, the published data on a particular motor stated a full load speed of 1740 rpm and, indeed, this was also printed on the outside of the box in which the motor was shipped. However, upon inspection of the nameplate, the nominal full load rpm was actually 1760 (see Table 5).

Table 5. Catalog Data vs. Nameplate Data

hp	Catalog rpm	Name-plate rpm	Catalog Efficiency	Name-Plate Efficiency
10	1745	1755	90.5%	91.7%
15	1745	1770	90.4%	93.0%
15	1740	1760	92.5%	92.5%
40	1780	1775	94.0%	94.5%
50	1780	1755	94.0%	94.5%
100	1775	1780	95.5%	95.8%

Parallel Pump Measurements. When there are two or more pumps in a parallel flow configuration, it is necessary to measure the pumps while operating independently. While measuring a three, 20 HP pump parallel flow configuration, it was discovered that the tests with one, two, and all three pumps operating resulted in significantly different operating characteristics. The power on pump A with all three pumps running required 13.3 kW. The same pump with only two pumps running required 15.4 kW. Finally, the power requirement went to 19.0 kW for pump A running alone. This 43% increase in required power significantly affects the measurements.

Though not all parallel pump configurations will show this much disparity (indeed, some showed no change at all), the best method is to measure one pump at a time. If measuring one pump at a time is not possible, then the before and after tests must be conducted with the same number of pumps operating.

Energy Efficient Motor Selection

After the candidate motor has been properly measured and the operating characteristics identified, there are additional issues to consider.

Annual Operating Hours

As can be expected, motors with low annual operating hours will not be as economically feasible as others with relatively high run time. There is no rule for determining the minimum annual run time for cost-effectiveness. Each motor must be considered on an individual basis.

The motor's kW requirements, load, and run time, considered in association with the cost of electricity are all integrally related. Changes in any one of these characteristics can significantly affect the overall cost-effectiveness of the energy efficient motor application. The best solution is to plug the numbers in the formulas provided in this paper and calculate the savings potential considering all the aspects.

Since the annual run time has a significant effect on the cost analysis, it's important to estimate the time as closely as possible. It was discovered in this program that the run time was the single most difficult number to estimate accurately. An energy management system with pump and fan control can be useful in determining daily run time for each season which can then be aggregated for the year. Naturally, it's usually best to be conservative in the estimate.

Note, however, that the run time will need to be significantly more to justify radically increased costs; when downsizing, for example. In contrast, low annual operating hours will likely justify the purchase of an energy efficient motor as a replacement for an existing beyond repair motor. The incremental cost of most energy efficient motors over standard motors will usually have a very short simple payback period.

Standard vs. Efficient Motors

It is also necessary to be cautious when selecting the energy efficient motor replacement. Many motors labeled "efficient" by the manufacturer are less efficient than other manufacturers' "standard" motors. An actual example is cited in Table 6:

Table 6. Standard vs. Efficient Motors

Catalog Description	Manuf.	Full Load Efficiency	List Price
Prem Effic	Brand X	88.8%	$1535
Std Effic	Brand Y	91.0%	$941

Always look at the actual efficiency and full load rpm data for comparisons. Remember, too, to inspect the nameplate upon receipt of the motor. It will most often be different than the catalog data.

Formulas

There are two relatively important formulas regarding the energy efficient motor selection. The first is a very simple formula for determining the amp load of a motor. The second is a relatively complex, but complete, formula used in this program for comparing the life cycle cost savings of two or more motors.

The amp load formula.

$$\frac{\textit{Measured true rms amps}}{\textit{Nameplace f.l. amps}} = \textit{load}$$

Though there are reported to be more accurate measurement strategies for determining motor load using amperage (Lobodovsky, 1994), this simple method requires no additional work; like disconnecting the load from the motor, for example. In the 60% to 80% loaded and up range (where most HVAC motors will be), the simple formula will usually be within 10% of the actual load[5]. As the motor load approaches 100%, the difference becomes increasingly less.

The Life Cycle Cost Savings Formula. The second formula requires some study. For this program it was necessary to take into account all of the parameters discussed here. This formula was developed specifically to compare new motor selections to one another.

where:

LCS	life-cycle cost savings
HP	load on motor in horsepower
E_{ex}	estimated existing motor efficiency
E_{eff}	new energy efficient motor nameplate efficiency
RPM_{eX}	nameplate full load rpm of existing motor
RPM_{efl}	nameplate full load rpm of new motor
hrs/year	annual operating hours of motor
$/kWh	electricity cost in dollars per kWh
$\$E_{eff}$	cost of new energy efficient motor

Summary/Recommendations

Measuring HVAC motors in the field is not a science; in fact, far from it. The dynamics of centrifugal pump and fan loads are complex and constantly changing, making energy savings projections analogous in most cases to shooting at a moving target. Accuracy and repeatability of field measurements, especially on individual motors, is rarely possible. The accuracy of field measurements (and generally the accuracy of the resultant energy calculations) increase with increased quantity of motors included in the study.

From the lessons learned in this empirically-oriented program, the following recommendations can be made:

Measure each existing motor before attempting to estimate savings. The true rms current is required to determine load, true kW is required to determine power. Do not attempt to apply data from one motor to another.

After the initial measurements of the existing motors for savings projections are complete, another measurement of the existing motors should be done immediately before changeout. Then measure the new motor immediately after startup. The data from this program indicates that the dynamics of pump and fan systems change over time (even on "constant volume" systems), so the less time between field measurements the more accurate the numbers.

When possible, measure the fluid pressure at the outlet of the pump or fan when measuring motors (before and after). This will indicate if the load has changed between measurements.

Always consider the effects of motor speed on power requirements.

Do a cost analysis for each motor.

Do not rely on the slip method for determining motor load. Use one of the amperage methods for determining load.

For motors less than 1/2 loaded, consider downsizing. Remember to add the cost of transition plates, couplings, heaters, breakers and any other motor specific change.

Do not rely on catalog data. Once a motor is selected, check the nameplate data (especially efficiency and rpm) to be certain the motor is right for the application.

Have a very good estimate of annual operating hours. No matter how good the field measurements and how accurate the calculations, if the estimated operating hours are not close to the actual operating hours, the energy savings and life-cycle cost analysis will adversely affected—often to a large degree. If a guess is required, make it conservative.

Measure the new motor (especially kW) when installed to determine the actual savings. Compare this to the projected savings.

Acknowledgments

The Arizona Department of Administration provided the personnel to facilitate the motor field measurements.

General information on motor operating characteristics was obtained from the Washington State Energy Office MotorMaster program and User's Guide.

Endnotes

1. The slip load and amp load were not reasonably close. In some cases, the measured speed was less than the full load speed, indicating a motor in excess of 100% loaded; but the measured amps were less than the full load amps, indicating a motor not fully loaded.

2. All dynamometer testing is courtesy of Reliance Electric in Phoenix, AZ (1993).

3. A Dranetz Model 8000-2 energy analyzer was used for all measurements.

4. Beaty, Wallace, Manager of Testing Laboratory, Baldor Electric Co., Fort Smith, AR; per phone conversations 1993, 1994.

5. Energy Office observations from tests and measurements.

6, Reliance Electric, data for a typical XE motor, 1991.

References

Electrical Apparatus Service Association (EASA). 1992. *Guidelines for Maintaining Motor Efficiency During Rebuilding*. Tech. Note No. 16, EASA Engineering Committee, EASA, St. Louis, MO.

Lobodovsky, K., "Motor Improvement Programs: Tracking Performance, Fine-tuning Maintenance." *Maintenance Solutions,* January/February 1994, pp. 16-7.

Bonneville Power Administration (BPA), *High Efficiency Motor Selection Handbook,* October, 1990, pp. 21.

Karasik, Igor J., *Pump Handbook,* McGraw-Hill Inc., 1976, pp. 2-131 to 2-142.

Spitzer, David W., *The Application of Variable Speed Drives,* Instrument Society of America, 1987, pp. 25.

Engineered Systems, March, 1993, pp. 44-48.

Stebbins, Wayne L., *Engineer's Digest,* June 1993, letter to the editor, pp. 31.

Montgomery, David, "Testing Rewinds to Avoid Motor Efficiency Degradation," *Energy Engineering,* Vol. 86, No. 3, 1989, pp. 24-40.