CHAPTER 6. ENERGY USE CHARACTERIZATION

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CHAPTER 6. ENERGY USE CHARACTERIZATION

6.1 INTRODUCTION

A key component of the life-cycle cost (LCC) and payback period (PBP) calculations described in chapter 8 is the savings in operating cost customers would realize from more energy efficient products. Energy costs are the most significant component of customer operating costs, with maintenance and repair costs the other contributors. DOE uses annual energy use, along with energy prices, to establish energy costs at various energy efficiency levels. This chapter describes how DOE determined the annual energy use of small electric motors.

6.2 ENERGY USE ANALYSIS FOR SMALL ELECTRIC MOTORS

6.2.1 Introduction

The energy use by small electric motors derives from three components: energy converted to useful mechanical shaft power, motor losses, and reactive power. Motor losses consist of I^2R losses (both stator and rotor), core losses, stray losses and friction and windage losses.[1] Core losses and friction and windage losses are relatively constant with variations in motor loading, while I^2R losses increase with the square of the motor loading. Stray losses are also dependent upon loading. DOE models the I^2R losses and stray losses as load-dependent losses.

6.2.2 Motor Losses

DOE obtained estimates of motor losses from estimates of the performance of the specific motor designs that it developed in the engineering analysis. To determine the annual energy use in kilowatt-hours (kWh), DOE adjusts the full-load losses using the estimate of the motor duty factor (hours of operation per year) and loading. Tables 6.2.1 through 6.2.3 present the losses as a function of loading for each motor type and for each efficiency level analyzed by DOE. These efficiency levels correspond with designs analyzed in the Engineering Analysis. Total annual losses are proportional to duty factor. Annual energy losses E_{loss} is represented by the following equation:

$$E_{loss} = H_{op} \times Loss(L)$$

Where:

E_{loss}	=	annual energy consumed by motor losses;
H_{op}	=	the annual operating hours, also known as the duty factor;
$Loss(L)$	=	the losses of the motor at loading L; and
L	=	motor loading as a fraction of rated power.

Table 6.2.1 Losses vs. Loading, Polyphase Motors

Losses *(W)* vs. Loading *(%)* – Polyphase, 1 hp

EL	Space Constrained							Not Space Constrained						
	0%	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**	**0%**	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**
0	125.0	133.1	149.3	175.6	213.8	266.6	337.2	125.0	133.1	149.3	175.6	213.8	266.6	337.2
1	114.8	122.6	137.0	159.8	191.5	234.1	290.2	114.8	122.6	137.0	159.8	191.5	234.1	290.2
2	102.6	110.3	124.0	145.6	175.2	214.7	266.4	102.6	110.3	124.0	145.6	175.2	214.7	266.4
3	84.1	91.9	106.0	127.6	158.1	199.2	253.0	84.1	91.9	106.0	127.6	158.1	199.2	253.0
4	81.1	88.7	102.2	122.5	151.2	189.5	239.6	81.1	88.7	102.2	122.5	151.2	189.5	239.6
5 (4b)	55.2	62.9	76.9	98.3	128.3	168.9	222.3	56.6	64.2	77.9	99.0	128.6	168.1	219.9
6	45.8	53.1	65.8	85.8	112.9	148.6	194.9	50.3	57.5	69.9	88.4	113.5	146.8	189.5
7	41.3	48.5	61.0	79.4	105.0	138.6	181.9	47.1	53.9	65.3	81.2	103.5	131.6	167.3
8	27.3	34.4	47.0	65.2	90.9	124.3	167.1	44.3	50.6	60.4	73.8	91.3	113.2	140.0

Table 6.2.2 Losses vs. Loading, Capacitor-Start Induction Run Motors

Losses *(W)* vs. Loading *(%)* – Capacitor-Start Induction-Run, 0.5 hp

EL	Space Constrained							Not Space Constrained						
	0%	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**	**0%**	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**
0	221.0	223.9	232.5	248.2	271.9	306.3	354.7	221.0	223.9	232.5	248.2	271.9	306.3	354.7
1	192.2	192.0	200.7	216.1	239.1	272.2	318.6	192.2	192.0	200.7	216.1	239.1	272.2	318.6
2	173.8	170.9	179.5	194.2	215.7	246.3	289.2	173.8	170.9	179.5	194.2	215.7	246.3	289.2
3	155.5	149.9	158.7	173.5	195.4	226.7	270.4	155.5	149.9	158.7	173.5	195.4	226.7	270.4
4	119.5	110.7	119.6	134.0	155.5	185.9	228.1	123.7	118.9	126.6	138.8	155.9	179.0	210.7
5	104.9	103.4	111.9	125.6	146.2	174.6	214.2	110.4	108.1	116.0	128.3	147.1	172.5	207.2
6	86.1	90.2	99.2	114.7	137.5	170.2	216.5	95.6	96.8	103.8	114.7	134.2	155.7	183.4
7	61.1	61.0	70.0	85.2	107.4	139.3	184.7	88.0	75.3	82.1	92.7	107.6	125.3	148.6

Table 6.2.3 Losses vs. Loading, Capacitor-Start Capacitor-Run Motors

Losses *(W)* vs. Loading *(%)* – Capacitor-Start Capacitor-Run, 0.75 hp

EL	Space Constrained							Not Space Constrained						
	0%	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**	**0%**	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**
0	157.7	159.1	171.6	195.5	232.5	287.5	370.1	157.7	159.1	171.6	195.5	232.5	287.5	370.1
1	155.0	144.0	151.2	166.3	192.5	231.9	289.9	155.0	144.0	151.2	166.3	192.5	231.9	289.9
2	116.2	103.7	110.5	124.9	149.0	184.9	237.7	107.0	96.6	104.5	121.2	148.7	191.8	257.7
3	109.5	93.7	98.3	109.9	129.3	160.1	204.8	87.5	77.2	85.7	101.6	128.4	168.0	226.5
4	117.4	99.1	99.6	106.4	120.4	144.9	181.9	116.3	94.1	96.1	104.2	120.2	146.3	185.9
5	133.3	99.4	98.6	103.1	113.4	129.5	153.1	118.8	89.6	91.4	98.0	110.8	131.4	162.2
6	94.1	77.5	78.8	86.6	103.3	131.0	174.4	104.9	81.6	83.3	90.9	105.5	130.5	168.6
7	86.1	62.7	65.2	73.5	88.6	112.2	148.8	102.0	71.4	72.1	77.2	88.6	107.1	134.1
8	70.0	49.2	52.4	61.6	77.9	104.1	141.0	76.8	57.0	57.3	64.8	80.3	107.3	152.4

6.2.3 Reactive Power

In an alternating current power system, the reactive power is the root mean square (RMS) voltage times the RMS current, multiplied by the sine of the phase difference between the voltage and the current. Reactive power occurs when the inductance or capacitance of the load shifts the phase of the voltage relative to the phase of the current. While reactive power does not consume energy directly, it can increase losses and costs for the electricity distribution system. Motors tend to create reactive power because the windings in the motor coils have high inductance.

Alternating current power flow has three components: real power (*P*), measured in watts (W); apparent power (*S*), measured in volt-amperes (VA); and reactive power (*Q*), measured in reactive volt-amperes (VAr). The power factor is defined as *P*/*S*. In the case of a perfectly sinusoidal waveform, *P*, *Q* and *S* can be expressed as vectors that form a vector triangle such that: $S^2 = P^2 + Q^2$. This implies that the formula for reactive power as a function of real power and power factor is as follows:

$$Q = P * (1/PF^2-1)$$

Where:

Q	=	reactive power in reactive volt-amperes;
P	=	real power in watts;
PF	=	the motor's power factor;

DOE obtained motor power factor as a function of motor loading from estimates of the performance of the specific motor designs that it developed in the engineering analysis. Tables 6.2.4 through 6.2.6 present the power factor as a function of loading for each motor type and for each efficiency level analyzed by DOE.

Table 6.2.4 Power Factor vs. Loading, Polyphase Motors

Power Factor ***(kW/kVAr)*** **vs. Loading** ***(%)*** **– Polyphase, 1 hp**

EL	Space Constrained							Not Space Constrained						
	0%	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**	**0%**	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**
0	0.13	0.31	0.47	0.60	0.69	0.75	0.79	0.13	0.31	0.47	0.60	0.69	0.75	0.79
1	0.13	0.33	0.50	0.62	0.71	0.76	0.80	0.13	0.33	0.50	0.62	0.71	0.76	0.80
2	0.12	0.33	0.50	0.62	0.71	0.77	0.80	0.12	0.33	0.50	0.62	0.71	0.77	0.80
3	0.11	0.35	0.53	0.66	0.74	0.79	0.82	0.11	0.35	0.53	0.66	0.74	0.79	0.82
4	0.11	0.34	0.53	0.66	0.73	0.78	0.81	0.11	0.34	0.53	0.66	0.73	0.78	0.81
5 (4b)	0.08	0.31	0.51	0.64	0.73	0.78	0.81	0.07	0.29	0.47	0.60	0.69	0.75	0.79
6	0.06	0.29	0.48	0.62	0.71	0.77	0.80	0.07	0.32	0.52	0.65	0.74	0.79	0.82
7	0.06	0.32	0.52	0.66	0.74	0.79	0.82	0.07	0.32	0.52	0.66	0.74	0.79	0.82
8	0.04	0.28	0.48	0.62	0.71	0.77	0.80	0.06	0.28	0.46	0.60	0.69	0.75	0.79

Table 6.2.5 Power Factor vs. Loading, Capacitor-Start Induction-Run Motors

Power Factor *(kW/kVAr)* **vs. Loading** *(%)* **– Capacitor-Start Induction-Run, 0.5 hp**

EL	Space Constrained							Not Space Constrained						
	0%	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**	**0%**	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**
0	0.225	0.318	0.409	0.493	0.568	0.632	0.686	0.23	0.32	0.41	0.49	0.57	0.63	0.69
1	0.215	0.314	0.412	0.501	0.578	0.643	0.695	0.22	0.31	0.41	0.50	0.58	0.64	0.69
2	0.207	0.308	0.411	0.502	0.581	0.644	0.695	0.21	0.31	0.41	0.50	0.58	0.64	0.69
3	0.207	0.317	0.428	0.526	0.606	0.668	0.716	0.21	0.32	0.43	0.53	0.61	0.67	0.72
4	0.170	0.285	0.406	0.512	0.598	0.664	0.714	0.21	0.34	0.47	0.57	0.65	0.71	0.75
5	0.164	0.300	0.430	0.540	0.626	0.691	0.737	0.20	0.35	0.49	0.59	0.67	0.73	0.76
6	0.135	0.280	0.414	0.526	0.615	0.680	0.726	0.15	0.29	0.43	0.54	0.62	0.69	0.75
7	0.119	0.290	0.449	0.573	0.662	0.723	0.761	0.17	0.31	0.46	0.57	0.65	0.71	0.75

Table 6.2.6 Power Factor vs. Loading, Capacitor-Start Capacitor-Run Motors

Power Factor *(kW/kVAr)* **vs. Loading** *(%)* **– Capacitor-Start Capacitor-Run, 0.75 hp**

EL	Space Constrained							Not Space Constrained						
	0%	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**	**0%**	**25%**	**50%**	**75%**	**100%**	**125%**	**150%**
0	0.19	0.35	0.49	0.60	0.69	0.75	0.79	0.19	0.35	0.49	0.60	0.69	0.75	0.79
1	0.26	0.45	0.60	0.71	0.77	0.81	0.84	0.26	0.45	0.60	0.71	0.77	0.81	0.84
2	0.20	0.40	0.56	0.68	0.76	0.80	0.83	0.27	0.52	0.69	0.79	0.84	0.86	0.86
3	0.25	0.48	0.65	0.76	0.82	0.85	0.87	0.22	0.49	0.67	0.78	0.83	0.85	0.86
4	0.48	0.74	0.85	0.90	0.92	0.93	0.93	0.78	0.90	0.95	0.96	0.96	0.95	0.94
5	0.54	0.69	0.85	0.90	0.92	0.93	0.93	0.76	0.86	0.94	0.96	0.96	0.95	0.94
6	0.46	0.75	0.87	0.91	0.93	0.93	0.93	0.94	0.97	0.98	0.98	0.97	0.96	0.95
7	0.53	0.77	0.90	0.94	0.94	0.94	0.93	0.86	0.93	0.97	0.98	0.97	0.97	0.96
8	0.29	0.60	0.80	0.87	0.90	0.91	0.91	0.94	0.99	1.00	1.00	0.99	0.98	0.96

6.2.4 Motor Applications

The annual operating hours and loading of small electric motors depends on the application. For different types of motors, the market shares of different motor applications can vary.

As described in more detail in chapter 9 of this TSD, DOE drew upon several data sources to develop a model of the applications for which motors covered in this analysis are used: data collected by Easton Consultants in the preparation of the Small Motors Determination Analysis,[2] DOE's own analysis in the Determination and Framework stages,[3,4] U.S. Census reports, comments from interested parties (both written and at the preliminary analysis public meeting),[5] and interviews with experts in motor OEM industries.[6] Chapter 9 discusses an alternate application distribution submitted by NEMA and analyzed by DOE.

Table 6.2.7 summarizes the market shares for shipments of small electric motors by application based on DOE's analysis of the available data.

Table 6.2.7 Application Shares by Equipment Category

		Equipment Category		
No.	**Application**	**Polyphase**	**CSIR**	**CSCR**
1	Air and gas compressors	17.3%	14.9%	14.9%
2	Conveyors	13.3%	11.9%	11.9%
3	General industrial machinery	11.3%	12.5%	12.5%
4	Industrial and commercial fans and blowers	7.3%	6.9%	6.9%
5	Pumps and pumping equipment	50.7%	53.7%	53.7%
	TOTAL	100%	100%	100%

6.2.5 Loading

To calculate the annual kWh use at each efficiency level in each equipment class, DOE used the efficiencies and losses from the engineering analysis, along with estimates of operating hours. Since the losses of a motor depend on the motor loading, DOE estimated average motor loading in order to look-up the motor losses from the engineering data. DOE obtained motor loading as a function of motor application from the determination analysis for the applications that use equipment containing covered small electric motors, as shown in Table 6.2.8. DOE assumed that the motor loading distribution took the form of a normal distribution, centered on the average value, with a standard deviation equal to one fifth of the average loading.

Table 6.2.8 Motor Loading by Application

No.	Application	Loading
1	Air and gas compressors	85%
2	Conveyors	50%
3	General industrial machinery	70%
4	Industrial and commercial fans and blowers	80%
5	Pumps and pumping equipment	65%

6.2.6 Motor Hours of Operation/Duty Factor

DOE developed estimated distributions for the duty factor of motors for each application. See chapter 9 for a discussion of the applications that DOE analyzed for covered motors, and the fraction of small electric motor shipments for each application. DOE estimated the distribution of motor duty factors from data referenced in Nadel *et al.*[7] DOE approximated this distribution as a decaying exponential curve plus a percentage of motors that operate 8760 hours per year (that is, 100% of the time). Figure 6.2.1 shows the correspondence between this simple model and the data referenced in Nadel *et al*.

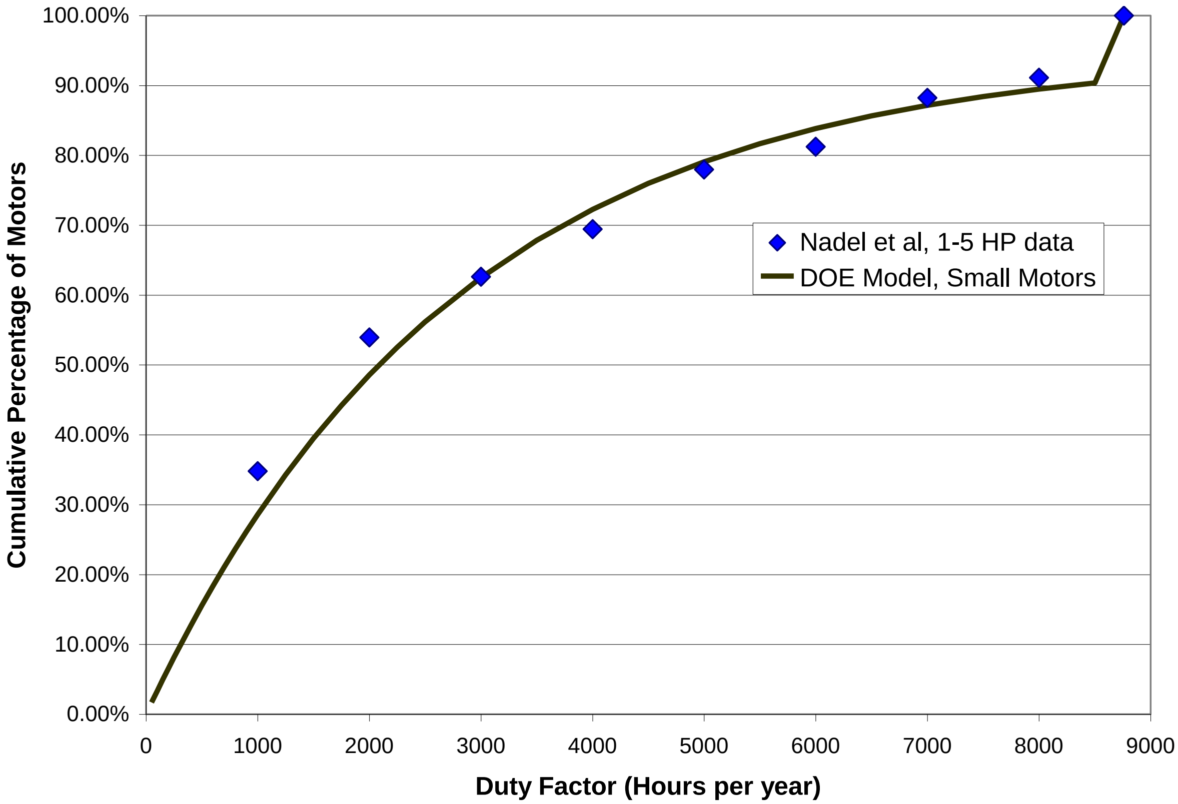

Figure 6.2.1 Comparison of DOE's Duty Factor Model with Nadel et al.

DOE then adapted this model for each of the five application areas analyzed as part of this rulemaking: pumps; conveyor, material handling, and packaging systems; air compressors; blowers and fans; and general industrial machinery. DOE used estimates for average and median hours of operation based on the 2006 Determination Analysis, along with comments from interested parties on the Preliminary Analysis, to develop distributions for each application.

Table 6.2.9 shows DOE's estimated median and mean hours of operation in each application, along with the percentage of motors that operate 100% of the time. Figure 6.2.2 shows the cumulative form of the discrete distributions DOE used in its Monte Carlo analysis. (The Monte Carlo analysis is described in chapter 8.)

Table 6.2.9 Median and Average Hours of Motor Operation by Application

Application	Median Annual Hours of Operation	Average Annual Hours of Operation	100% Run Time Motors (%)
Compressors	375	600	0
Conveyors	2000	3000	8
General Industry	1200	2000	4
Fans and Blowers	2825	4500	40
Pumps	1850	3000	12

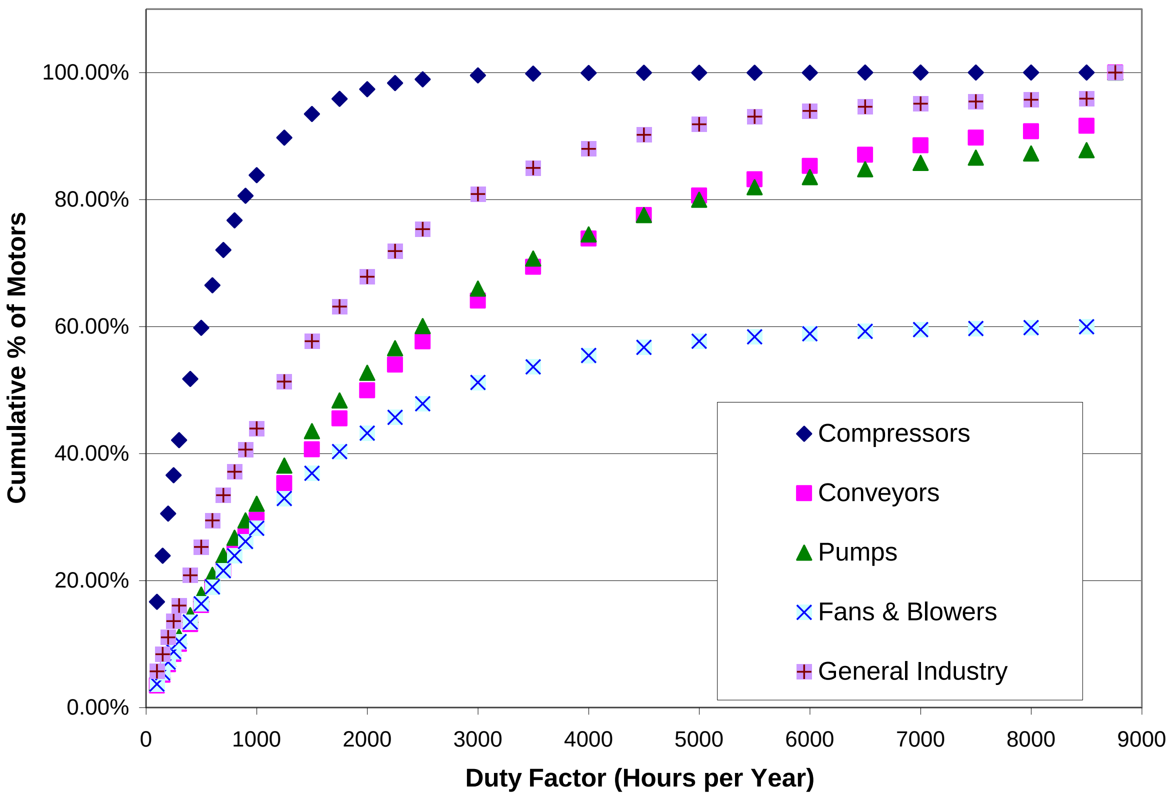

Figure 6.2.2 DOE Estimates of Duty Factor Distributions for Motors in Analyzed Applications

In comments submitted is response to the NOPR for this rulemaking, NEMA submitted alternate distributions of annual hours of operation in each motor application. (In addition, NEMA suggested another application area, Service Industry motors.) Table 6.2.10 shows NEMA's suggested data. In its LCC and NIA analyses, DOE analyzed alternate scenarios, as sensitivities, which incorporate NEMA's suggested hours of operation, application distribution, and the fraction of motor applications which are space constrained.

Table 6.2.10 NEMA-Proposed Median and Average Hours of Motor Operation by Application

Application	Median Annual Hours of Operation	Average Annual Hours of Operation	100% Run Time Motors (%)
Compressors	100	200	0
Conveyors	2000	3000	0
General Industry	1200	2000	4
Fans and Blowers	2825	4500	10
Pumps	1850	3000	12
Service Industry	400	1000	2

6.3 ANNUAL ENERGY USE

Depending on the hours of operation and the loading (which are functions of the application) and the efficiency of the motor (which varies with the standard level), the annual energy use varies both by efficiency level and from motor to motor. Table 6.3.1 shows the average annual energy use as a function of efficiency level for the three representative product classes. In the table, the rated capacity of the representative motor from the product class is in parentheses. The average energy use estimates are from a calculation for a nationally representative distribution of motor applications, include both motor losses and the shaft power provided by the motor as described in chapter 8 of this TSD.

Table 6.3.1 Average Annual Electricity Use by Efficiency Level for Small Electric Motors (Using National Shipment-Weighted Distribution of Product Class Shipments)

Efficiency Level	Polyphase	CSIR	CSCR
	Energy Use (kWh/yr)	Energy Use (kWh/yr)	Energy Use (kWh/yr)
Baseline	1934	1265	2310
1	1883	1182	2208
2	1836	1125	2036
3	1775	1071	1965
4	1759	979	1979
5	1678	953	1959
6	1643	920	1923
7	1622	858	1873
8	1594	NA	1824

REFERENCES

1 National Electrical Manufacturers Association, NEMA Standards Publication: Information Guide for General Purpose Industrial AC Small and Medium Squirrel-Cage Inducation Motor Standards, NEMA, 1300 North 17th Street, Suite 1847, Rosslyn, VA 22209, 2002.

2 The work by Easton Consultants is summarized in Appendix B of *Determination Analysis Technical Support Document: Analysis of Energy Conservation Standards for Small Electric Motors*, June 2006 <http://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/small_motors_tsd.pdf>

3 *Determination Analysis Technical Support Document: Analysis of Energy Conservation Standards for Small Electric Motors*, June 2006 <http://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/small_motors_tsd.pdf>

4 Energy Conservation Standards Rulemaking Framework Document for Small Electric Motors <http://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/small_motors_framework_073007.pdf>

5 Transcript of Public Meeting on Energy Conservation Standards for Small Electric Motors, January 30, 2009, <http://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/transcript_small_motors_standards_meeting.pdf>

6 Joe Evans. PentAir Water Pumps, personal communication, March 5, 2009.

7 Nadel, S. ; Elliott, R.N. ; Shepard, M. ; Greenberg, S. ; Katz, G. ; Almeida, A. de, *Energy-efficient motor systems: A handbook on technology, programs, and policy opportunities, 2nd edition.* 2000. American Council for an Energy-Efficient Economy, Washington, DC (US).