APPENDIX 7-C. CALCULATION OF FURNACE BLOWER FAN ENERGY CONSUMPTION

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APPENDIX 7-C. CALCULATION OF FURNACE BLOWER FAN ENERGY CONSUMPTION

7-C.1 INTRODUCTION

The electricity consumption (and overall efficiency) of a blower motor depends on the speed at which the motor operates, the external static pressure difference across the blower, and the airflow through the blower. To calculate blower-motor electricity consumption, DOE determined the operating conditions (the pressure and airflow) at which a particular furnace in a particular housing unit will operate. These operating conditions can be graphically displayed as the intersection of a system curve of the ducts in the housing unit (which plots the airflow across the supply and return air ducts as a function of static pressure) with the fan curve of the furnace (which plots the airflow through the furnace as a function of static pressure). The intersection of these two curves is the airflow and the static pressure at which the furnace will operate in that housing unit.

Furnace fan curves, reported as tables of airflow rise versus static pressure through the furnace, are available from manufacturers in the product literature for each furnace. Some of the manufacturers also supply blower-motor input power as a function of static pressure across the furnace.

Air power is calculated from the air speed through the furnace and the pressure rise across the furnace. The overall air-moving efficiency is air power divided by the electric power to the blower motor. All the electric power of the blower motor eventually is converted to heat that contributes to meeting the building heating load.

7-C.2 SYSTEM CURVES

The system curve of the air-distribution system is a graphical representation of the airflow through the supply and return ducts in a house for different static pressure. The airflow and pressure drop at which the furnace will operate can be determined by the intersection of the system curve of the house and the fan curve of the furnace circulating air blower.[1]

The Department modeled system curves as quadratic curves, which is standard in heating, ventilation, and air conditioning (HVAC) design and fan selection handbooks.[2] The curves are based on Bernoulli's equations for fluid flow and are expressed as the following equation:

$$Q = \sqrt{\frac{P}{\alpha}}$$

where:

Q = airflow (cfm),
P = static pressure (in.w.g.), and
α = a constant coefficient.

The Department selected the coefficient in the system curve equation for each housing unit. It randomly sampled a coefficient from one of four distributions, depending on the nominal maximum airflow of the virtual model furnace selected for that housing unit. The Department designed each distribution so that 10 percent of samples would have static pressures below 0.5 in.w.g., and 1 percent of the samples would have static pressures greater than 1 in.w.g at the nominal maximum airflow. This is in line with several field studies.[3] To keep the system curves from clumping at the higher pressures, the Department used a log-normal distribution of values of the coefficient. See Figure 7-C.2.1 for an example of a plot of system curves intersecting a furnace fan curve.

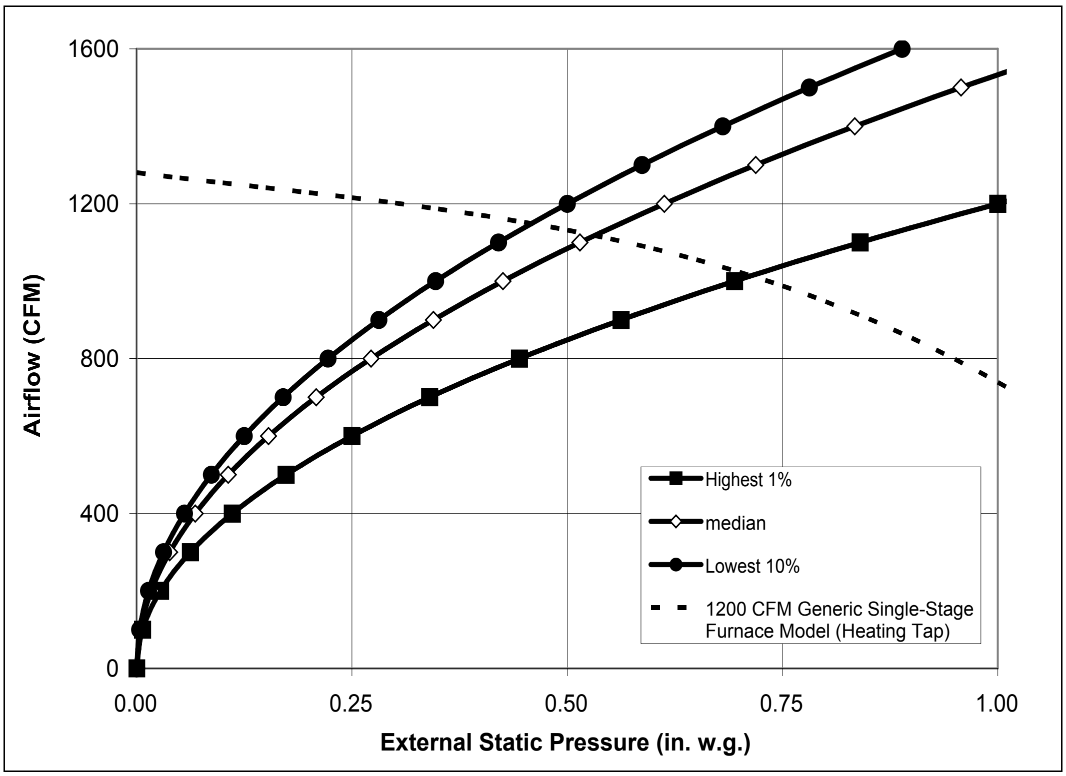

Figure 7-C.2.1 Sample of System Curves with a Typical Fan Curve

7-C.3 FURNACE FAN CURVES

Depending on the resistance (measured as static pressure) of the supply and return air ducts, a furnace will move more or less air. When these airflow values are plotted graphically against pressure, they are referred to as fan curves.

The Department developed fan curves for the single-stage (High Fire modes) virtual furnace models and for two-stage (High Fire and Low Fire modes) by fitting the manufacturer airflow and pressure data points from the basic model furnaces[4, 5, 6, 7, 8, 9, 10] to a second-order polynomial. The Department did this separately for each of the four nominal air handler sizes. The CFM for PSC blower motors is given by the following equation:

$$CFM = m_0 + m_1 \times (P) + m_2 \times (P^2) \quad \textbf{Eq. 1}$$

where,

CFM	=	airflow in CFM reported by manufacturer,
$m_{0,1,2,and\ 3}$	=	coefficients derived from 2nd degree polynomial approximation (see Table 7-C.3.1 for actual coefficient values), and
P	=	external static pressure (in.w.g.).

Table 7-C.3.1 Coefficients for CFM equation for PSC motors

	High Fire (Single-Stage)			**Low Fire**		
	m_0	m_1	m_2	m_0	m_1	m_2
2-ton	840.8	-42.5	-494.9	712.8	-87.7	-400.4
3-ton	1158.0	-12.1	-507.2	930.6	99.1	-527.3
4-ton	1522.7	-40.3	-527.0	1158.6	36.1	-463.6
5-ton	1877.5	-102.8	-485.0	1469.0	37.8	-453.2

Figure 7-C.3.2 shows an example of a CFM curve for a 3-ton Non-Condensing Single-Stage Furnace fitted with the manufacturers' raw data.

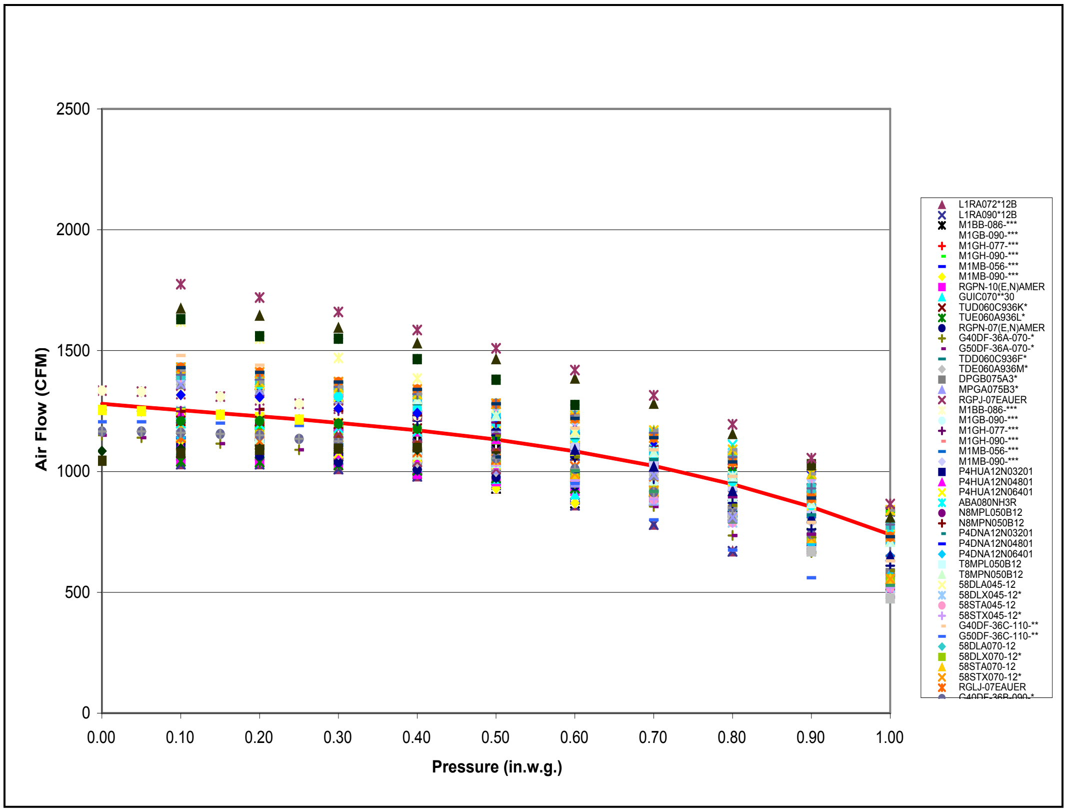

Figure 7-C.3.2 Example Fit of CFM for 3-ton Single-Stage (High Fire) Furnace

Figure 7-C.3.3 shows the fan curves for PSC furnaces. Appendix 7-G contains the data on the basic models that were used to develop these fan curves.

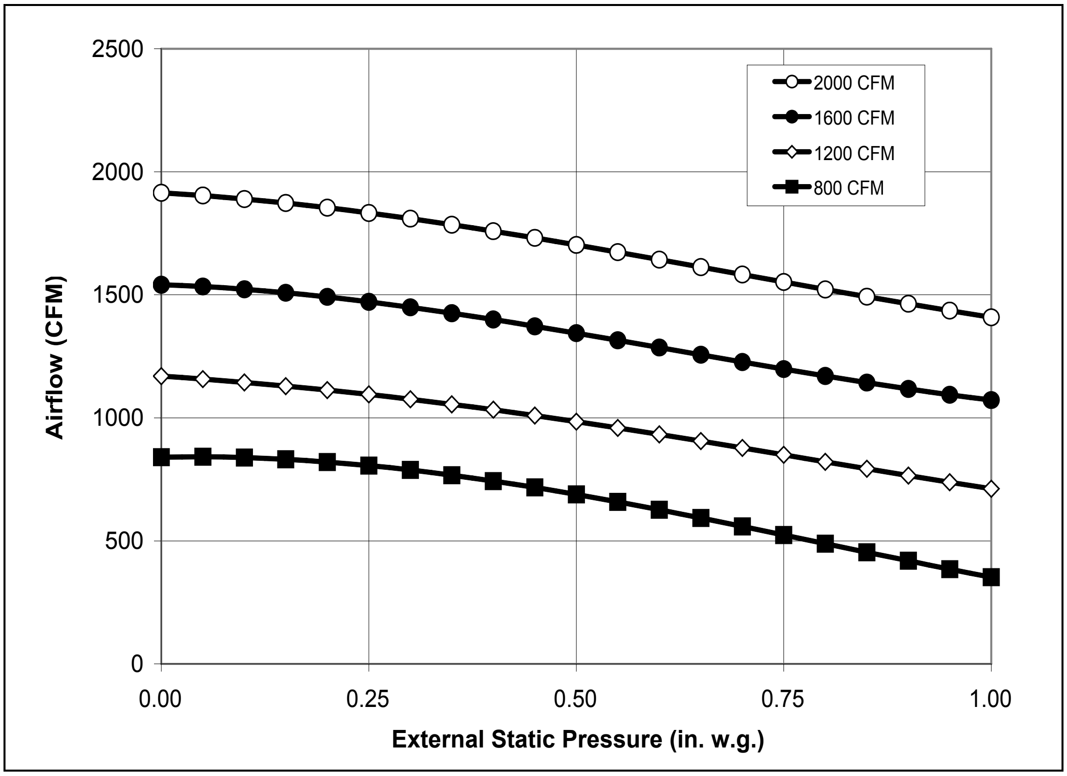

Figure 7-C.3.3 Fan Curves for Single-Stage Virtual Model Furnaces

The two-stage and continuous modulating design options in this analysis use brushless permanent magnet motors (or sometimes referred as Electronically Commutated Motors (ECM)). Unlike PSC motors, these motors are electronically commutated and the speed they operate at can be varied across a wide range. These motors are controlled to operate the blower fans at a wide variety of air flows and static pressures. In furnaces with these motors currently on the market, the controls are designed to provide a near constant air flow across the entire range of pressures at which they operate.

Because of the versatility of the motors, manufacturers only offer furnaces with blowers nominally designed for operation with five-ton and three-ton air conditioners. The manufacturers provide control options to decrease the airflow for installations that use smaller air conditioners.

To develop fan curves for furnaces with ECM motors, the Department fit quadratic curves through the air flow and pressure data points reported by manufacturers.[11, 12, 13, 14, 15, 16, 17] DOE did this separately for high-fire and low-fire operation. See Figure 7-C.3.4 through Figure 7-C.3.5 for charts showing the fit lines. Table 7-C.3.2 shows the coefficients for two-stage and continuous modulating furnaces with ECM motors below. Data from the basic models that were used to develop these fan curves is shown in Appendix 7-H, Determination of Basic Furnace Models.

$$CFM = m_0 + m_1 \times (P) + m_2 \times (P^2)$$

where,

CFM	=	airflow in CFM reported by manufacturer,
$m_{0,1,\ and\ 2}$	=	coefficients derived from 2nd degree polynomial approximation (see Table 7-C.3.2 for actual coefficient values), and
P	=	external static pressure (in.w.g.).

Table 7-C.3.2 Coefficients for CFM equation for Two-Stage and Continuous Modulating furnaces with ECM motors

	High Fire			**Low Fire**		
	m_0	m_1	m_2	m_0	m_1	m_2
2-ton	785.1	46.9	-135.1	580.7	17.5	-81.5
3-ton	1043.2	23.5	-101.1	779.3	2.6	-64.0
4-ton	1326.2	57.6	-61.9	946.7	6.5	13.8
5-ton	1571.9	5.6	-30.5	1160.9	-17.7	1.1

To be consistent with the analysis it did for the single-stage furnaces with PSC blower motors, the Department created virtual models for furnaces intended to act as air handlers for four and two ton air conditioners, even though these are not currently offered by manufacturers. To generate the fan curves for the virtual furnaces intended to be used with 4 ton air conditioners, DOE calculated the average of the slopes and intercepts of the virtual furnaces with air handler for 5 ton and 3 ton air conditioners. This was done separately for high and low fire operations for non-condensing and condensing furnaces.

For the virtual furnace models intended to operate with two-ton air conditioners, the fan curves were created by extrapolating the values for the slopes and intercepts of the virtual furnace models with air handlers intended to operate with three-ton and five- ton air conditioners. This was also done separately for high fire and low fire operation for both non-condensing and condensing furnaces. See Figure 7-C.3.4 through Figure 7-C.3.5 for charts showing the fan curves for these air handlers.

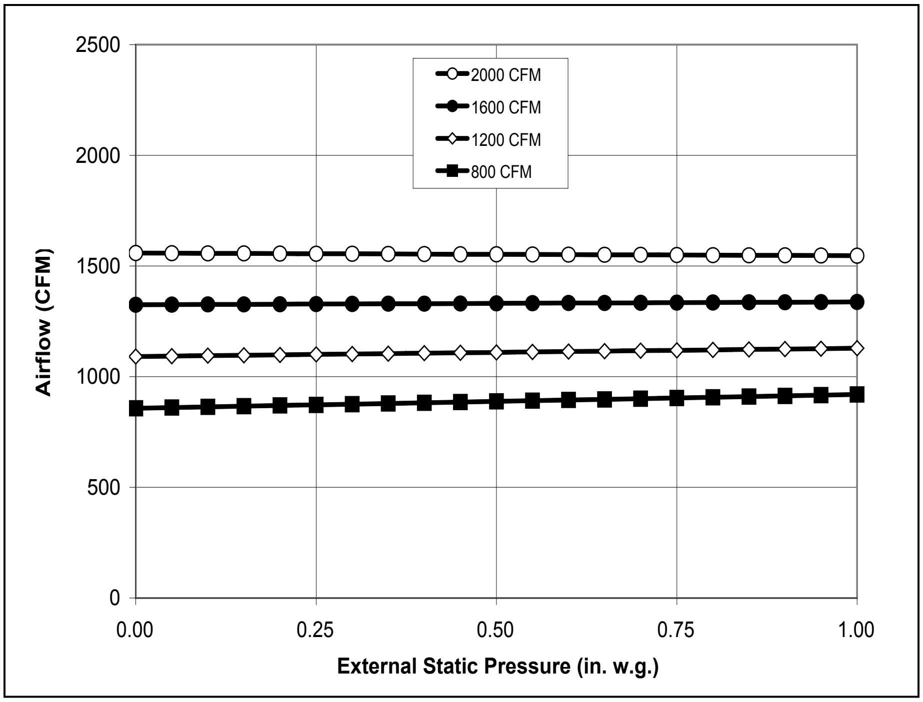

Figure 7-C.3.4 Fan Curves for Two-Stage Virtual Model Furnaces – High Fire

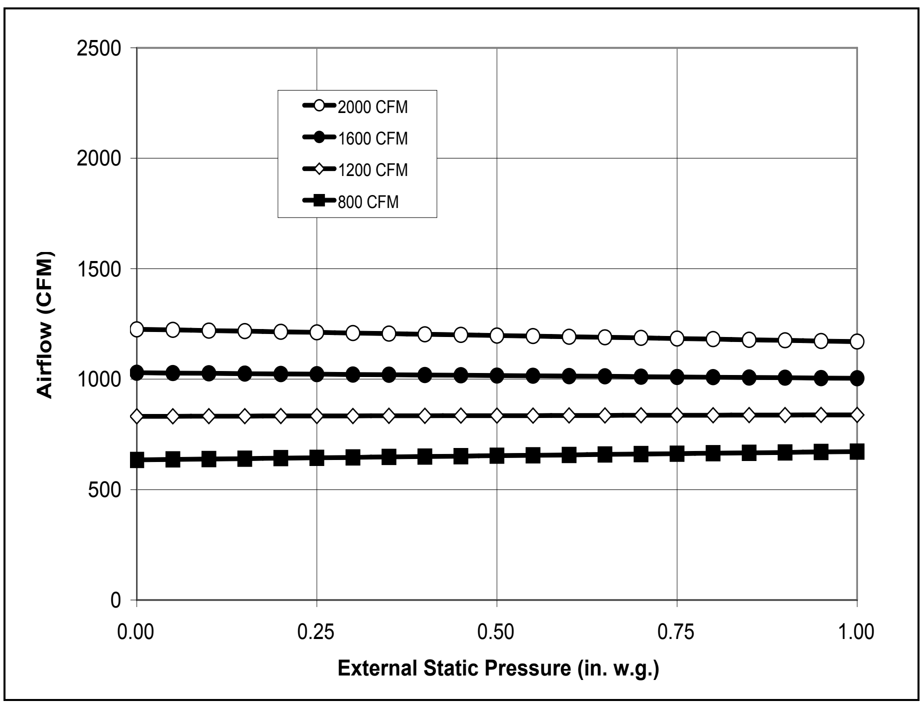

Figure 7-C.3.5 Fan Curves for Two-Stage Virtual Model Furnaces – Low Fire

7-C.4 FAN POWER

Once the operating point of air flow and static pressure is determined by finding the intersection of the fan curve and the system curve, the watts per cubic feet per minute (CFM) of airflow are determined using the equations developed in this appendix. The power consumption of the fan at this operating condition, BE, is calculated by multiplying the Watts/CFM by the CFM at the operating point:

$$BE = \left(\frac{Watts}{CFM}\right) \times Q$$

where,

BE	=	circulating air fan electrical energy consumption (watts),
Watts/CFM	=	determined below, and
Q	=	airflow (cfm).

For furnaces with air handlers with permanent split capacitor (PSC) blower motors, one manufacturer reports watts across a range of pressures. For these models, the Department divided watts at these pressures by air flow in CFM at these same pressures. These values of watts per CFM across a range of pressures were fit to a second order polynomial for the basic furnace models made by the manufacturer. The Department did this separately for each of the four nominal air handler sizes. The watts per CFM for PSC blower motors is given by the following equation:

$$\frac{Watts}{CFM} = m_0 + m_1 \times (P) + m_2 \times (P^2)$$

where,

Watts/CFM	=	blower electricity consumption in watts reported by manufacturer divided by the airflow in CFM at the same static pressure,
$m_{0,1,and\ 2}$	=	coefficients derived from 2^{nd} degree polynomial approximation (see Table 7-C.4.1 for actual coefficient values), and
P	=	external static pressure (in.w.g.).

Table 7-C.4.1 Coefficients for W/CFM equation for PSC motors

	High Fire (Single-Stage)			Low Fire		
	m_0	m_1	m_2	m_0	m_1	m_2
2-ton	0.395	-0.161	0.258	0.384	-0.140	0.332
3-ton	0.432	-0.209	0.185	0.425	-0.204	0.209
4-ton	0.416	-0.191	0.156	0.428	-0.195	0.152
5-ton	0.449	-0.124	0.096	0.449	-0.130	0.086

Figure 7-C.4.1 shows the Watts per CFM curve for 3-ton condensing single-stage furnace fitted to the manufacturers' data. A similar process of fitting curves to data was done for each nominal air handler size.

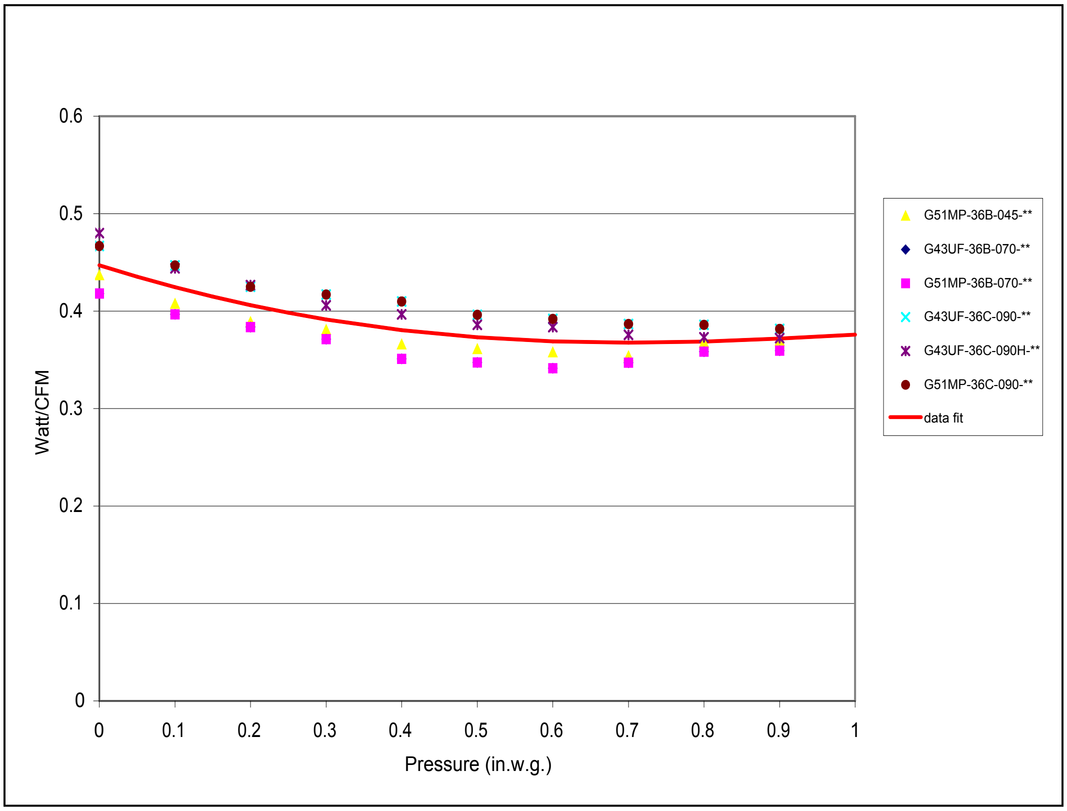

Figure 7-C.4.1 Example Fit of Watts/CFM for 3-ton Single-Stage Furnace

Figure 7-C.4.2 shows the fit curves of Watts/CFM for pressures from 0 in.w.g. to 1.0 in.w.g. Data from the models that were used to develop these fan curves is shown in Appendix H, Determination of Basic Furnace and Boiler Models.

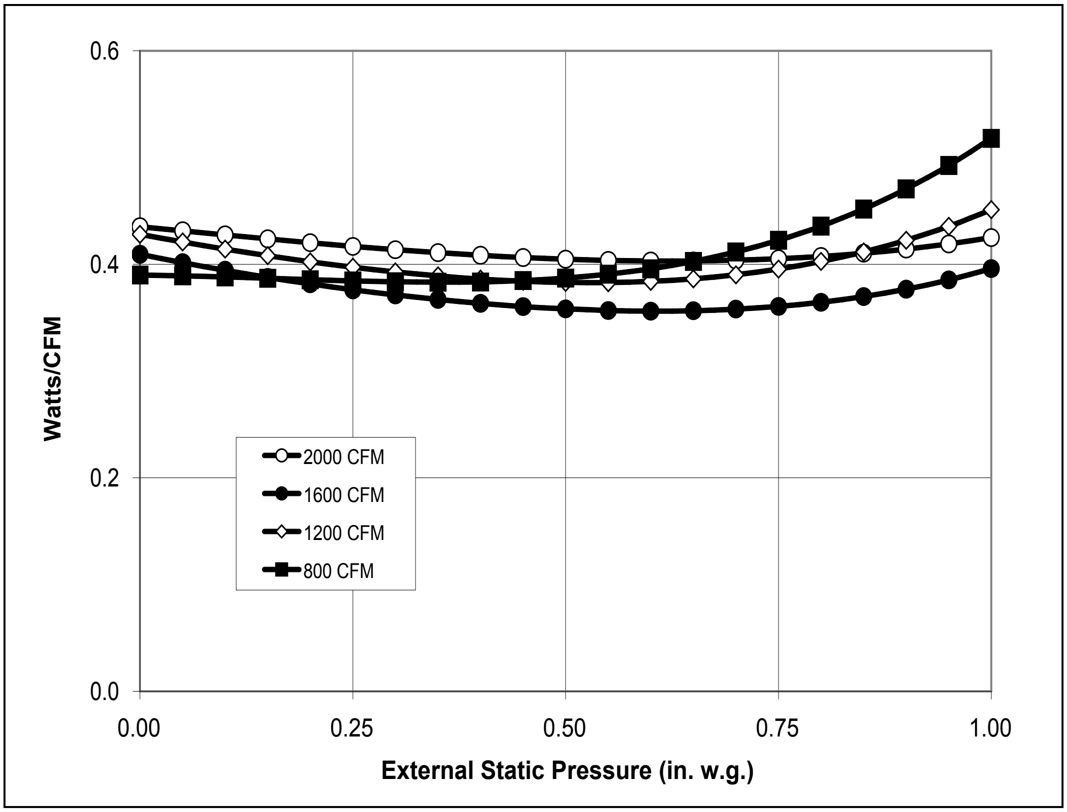

Figure 7-C.4.2 Watts/CFM vs. Pressure Curves for Single-Stage Virtual Model Furnaces

For the two-stage and continuous modulating furnaces with ECM motors, the Department calculated watts per CFM equations using data from basic models of several manufacturers. These data are in the reduced set of furnace models database.

This was done for basic model furnaces nominally designed for use with 3 ton and 5 ton air conditioners. The watts per CFM data points of these basic models were fit to straight lines using Equation 4. To be consistent with other analyses, the Department calculated the slope and intercept for the watts per CFM curves for furnaces intended to operate with 2 ton and 4 ton air conditioners by interpolating from the values for 3 ton and 5 ton air handlers. Figure 7-C.4.3 through Figure 7-C.4.4 show the lines for the basic models. Table 7-C.4.2 shows the coefficients for two-stage and continuous modulating furnaces with ECM motors using Eq. 3. Data from the models used to develop these fan curves is shown in Appendix H, Determination of Basic Furnace and Boiler Models.

$$\frac{Watts}{CFM} = m_0 + m_1 \times (P) + m_2 \times (P^2) \quad \textbf{Eq. 4}$$

where,

Watts/CFM = blower electricity consumption in watts reported by manufacturer divided by the airflow in CFM at the same static pressure,

$m_{0,1,\text{ and }2}$	=	coefficients derived from second degree polynomial (see Table F-C.4.2 for actual coefficient values), and
P	=	external static pressure (in. w.g.).

Table 7-C.4.2 Coefficients for W/CFM equation for Two-Stage and Continuous Modulating furnaces with ECM motors

	High Fire			Low Fire		
	m_0	m_1	m_2	m_0	m_1	m_2
2-ton	0.143	0.247	-0.048	0.090	0.239	0.005
3-ton	0.160	0.239	-0.029	0.100	0.240	0.003
4-ton	0.170	0.311	-0.084	0.104	0.251	0.012
5-ton	0.190	0.264	-0.029	0.117	0.246	0.004

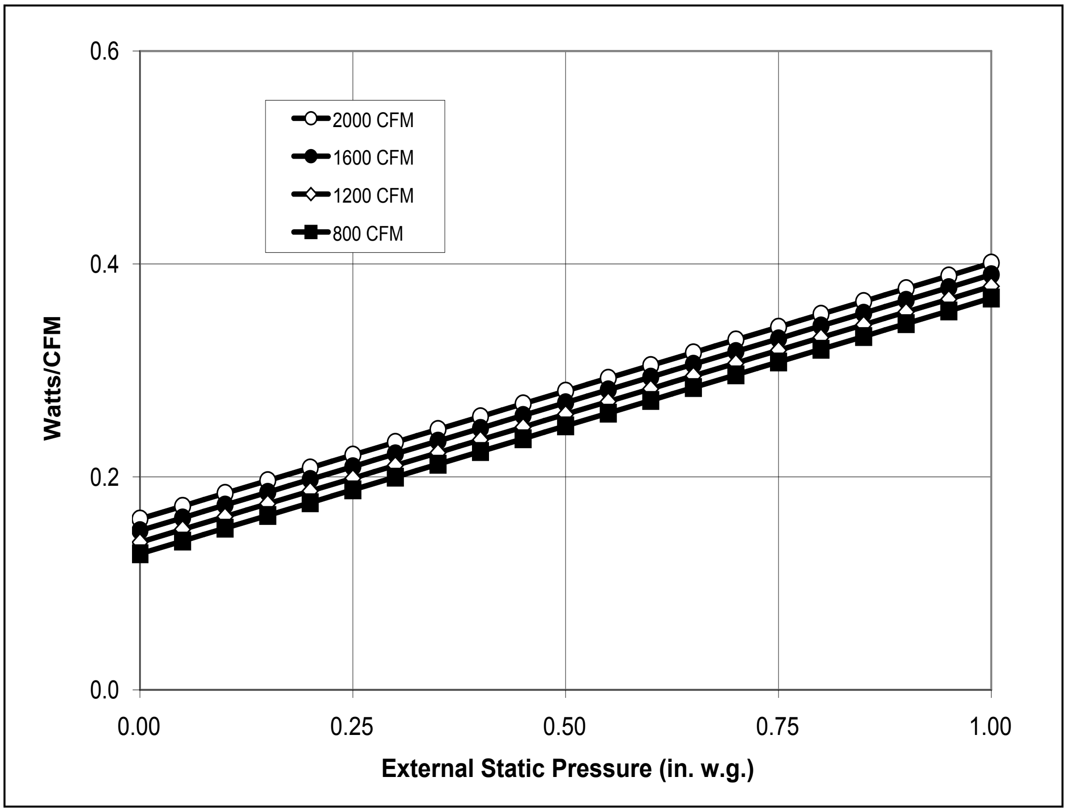

Figure 7-C.4.3 Watts/CFM vs. Pressure Curves for Two-Stage Virtual Model Furnaces – High Fire

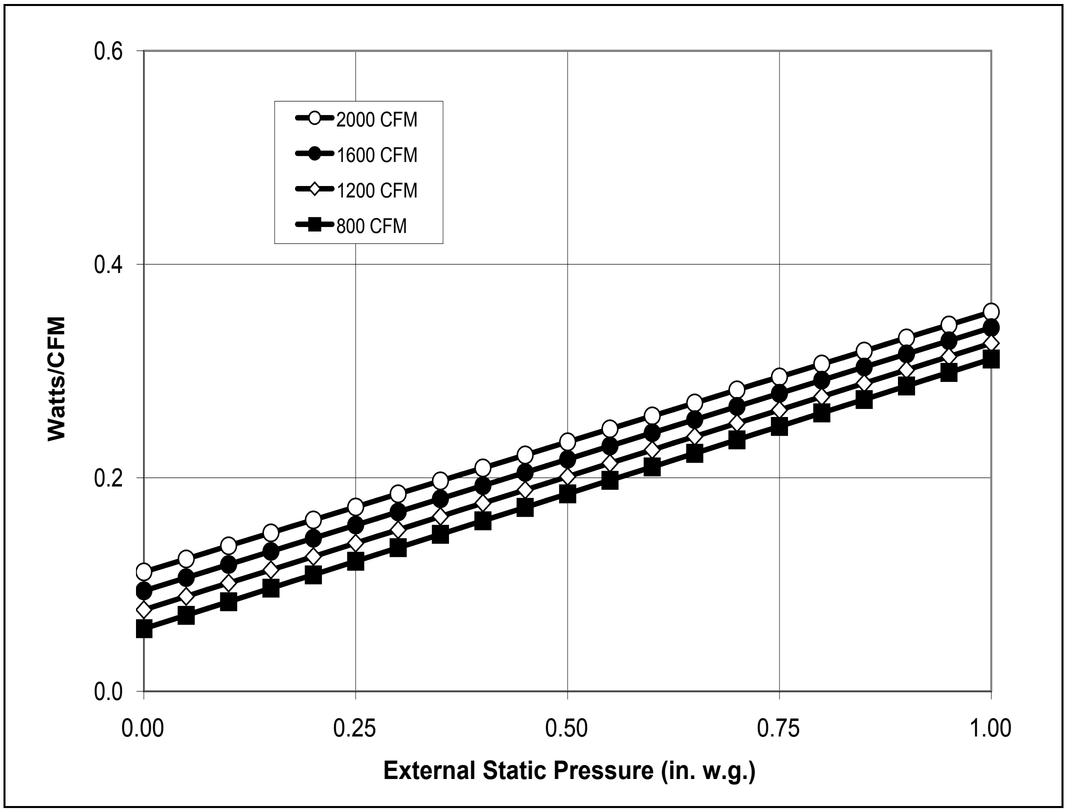

Figure 7-C.4.4 Watts/CFM vs. Pressure Curves for Two-Stage Virtual Model Furnaces – Low Fire

7-C.5 DETERMINATION OF FAN CURVES FOR EACH EFFICIENCY LEVEL AND PRODUCT CLASS

In order to generate the fan performance data used in the analysis DOE applied the following procedure (the 3-ton baseline PSC motor for non-weatherized (non-condensing) gas furnaces is used as an example):

STEP 1: Using the coefficients to generate for airflow (cfm) vs. pressure and watts/cfm vs. pressure curves at each airflow speed (heating, cooling, and continuous fan), DOE found the airflow cfm and watts per CFM at DOE's reference system curve external static pressure. For example, DOE's reference system curve external static pressure is 0.65 in.w.g at the maximum cooling airflow speed for non-weatherized gas furnaces. For the 3-ton baseline PSC motor for non-weatherized (non-condensing) gas furnaces the maximum airflow CFM was calculate to be 1158 cubic feet per minute.

STEP 2: Using the BE equation above, DOE multiplied the airflow times the watt/cfm at each pressure from Step 1 to calculate *BE* at each airflow speed (heating, cooling, and continuous fan) in terms of DOE's reference system curve external static pressure. For example, for the 3-ton baseline PSC motor for non-weatherized (non-condensing) gas furnaces *BE* was calculate to be 382 watts at heating, 495 watts at cooling, and 382 watts at continuous fan.

STEP 3: Using the calculated maximum airflow CFM and BE values at DOE's reference system curve external static pressure, DOE was able to calculate Furnace Efficiency Rating (FER) values. For example, for the 3-ton baseline PSC motor for non-weatherized (non-condensing) gas furnaces FER was calculated as 363.

STEP 4: The constant curve fit parameter (m_0) in the pressure and watts/cfm vs. pressure curves was then adjusted using an adjustment multiplier in order to match the FER values derived in the engineering analysis. For example, for the 3-ton baseline PSC motor for non-weatherized (non-condensing) gas furnaces the FER value derived in the engineering analysis was 380, so the adjustment multiplier to convert the FER value calculated in step 3 was calculated as 1.04.

Table 7-C.5.1 shows the airflow (cfm) vs. pressure coefficients determined for non-weatherized (non-condensing) gas furnaces (3-ton) at each efficiency level (EL). Figure 7-C.5.2 to Figure 7-C.5.4 show the resulting curves at various pressures and operating modes.

Table 7-C.5.1 Coefficients for CFM equation for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton

EL	Heating			Cooling			Continuous Fan		
	m_0	m_1	m_2	m_0	m_1	m_2	m_0	m_1	m_2
0	1158	-12	-507	1523	-280	-432	1158	-12	-507
1	1158	-12	-507	1523	-280	-432	931	99	-527
2	1059	269	-405	1277	198	-516	667	-117	-44
3	1139	-403	-62	1427	-323	-15	1001	-880	214
4	1043	24	-101	1203	8	-26	679	3	-64
5	1043	24	-101	1203	8	-26	679	3	-64

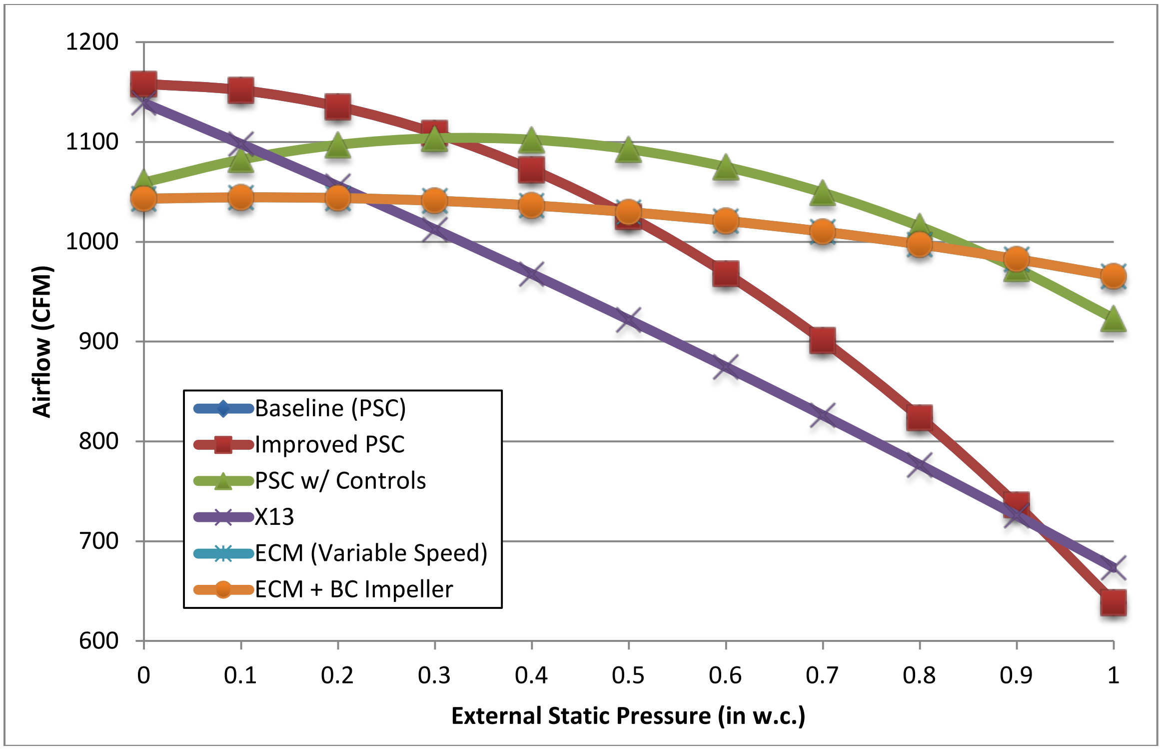

Figure 7-C.5.2 CFM Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Heating Mode)

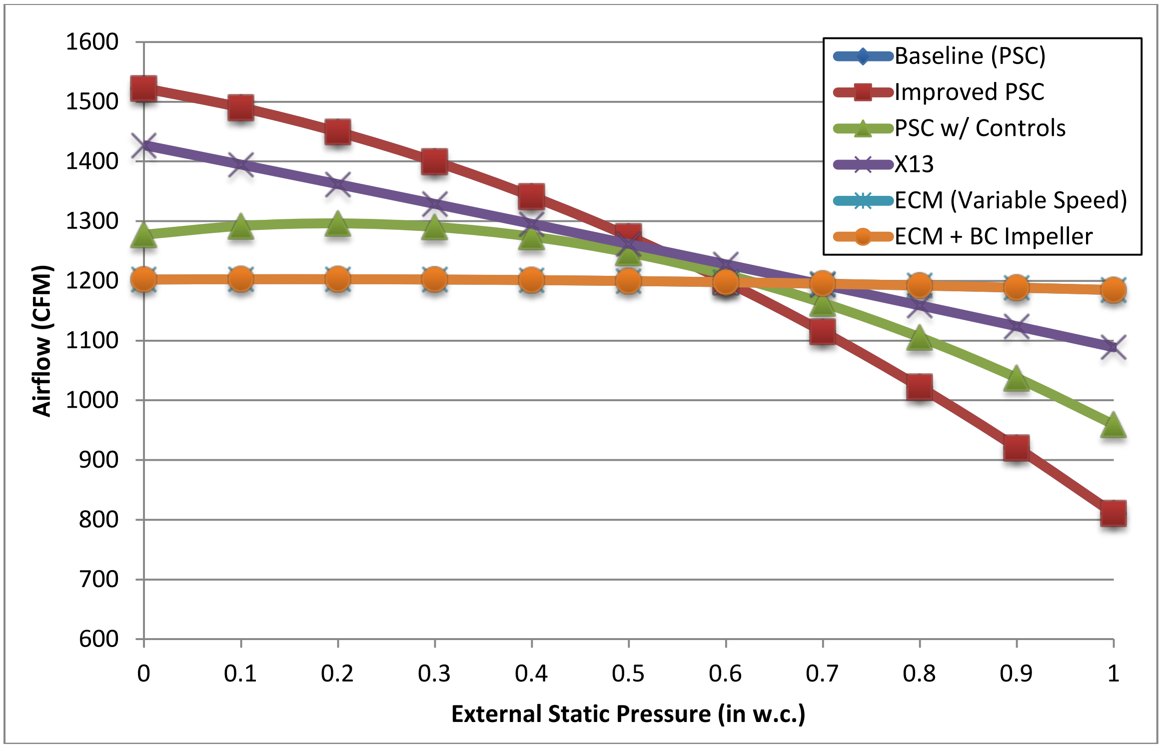

Figure 7-C.5.3 CFM Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Cooling Mode)

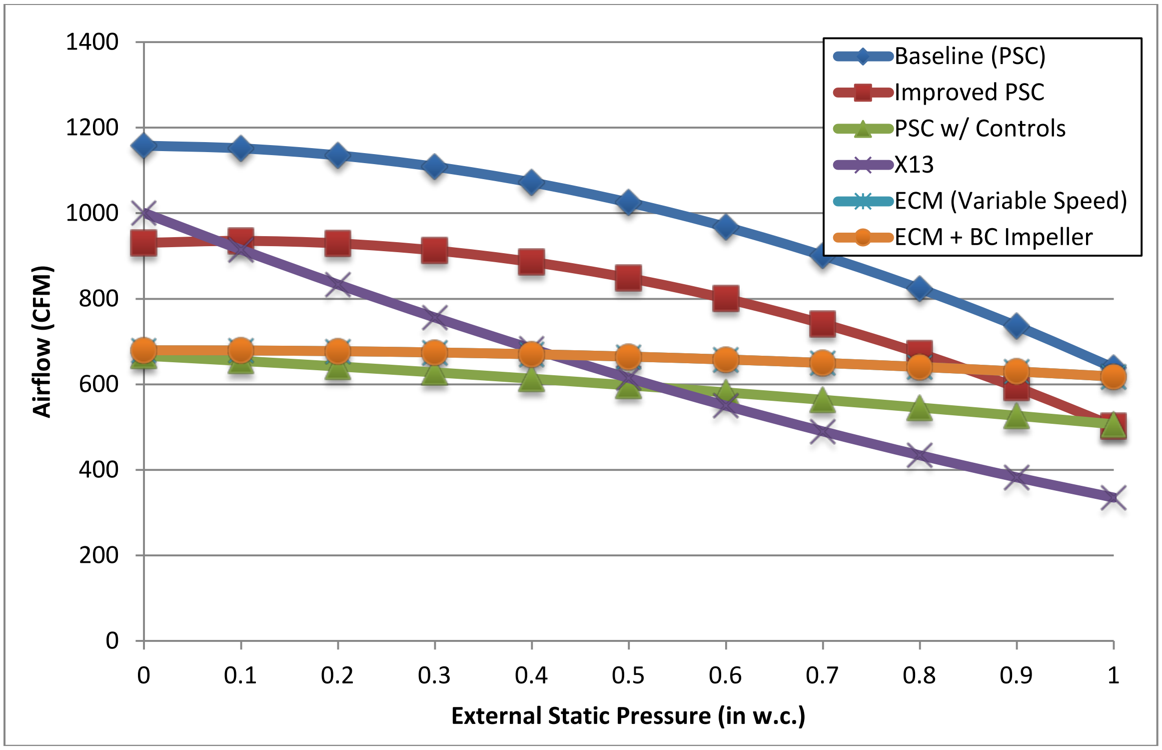

Figure 7-C.5.4 CFM Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Continuous Fan Mode)

Table 7-C.5.2 shows the watts/cfm vs. pressure curves coefficients determined for non-weatherized (non-condensing) gas furnaces (3-ton) at each efficiency level. Figure 7-C.5.5 to Figure 7-C.5.7 show the resulting curves at various pressures. Figure 7-C.5.8 to Figure 7-C.5.10 show the resulting Watts vs. pressure curves.

Table 7-C.5.2 Coefficients for Watts/CFM Equation for Non-Weatherized (Non-Condensing) Gas Furnaces, 3-Ton

EL	Heating			Cooling			Continuous Fan		
	m_0	m_1	m_2	m_0	m_1	m_2	m_0	m_1	m_2
0	0.45	-0.21	0.19	0.46	-0.12	0.15	0.45	-0.21	0.19
1	0.45	-0.21	0.19	0.46	-0.12	0.15	0.44	-0.20	0.21
2	0.30	0.16	0.02	0.35	0.16	-0.03	0.22	0.15	0.14
3	0.15	0.10	0.10	0.24	0.12	0.04	0.13	0.01	0.42
4	0.12	0.24	-0.03	0.13	0.29	-0.04	0.07	0.24	0.00
5	0.09	0.24	-0.03	0.10	0.29	-0.04	0.06	0.24	0.00

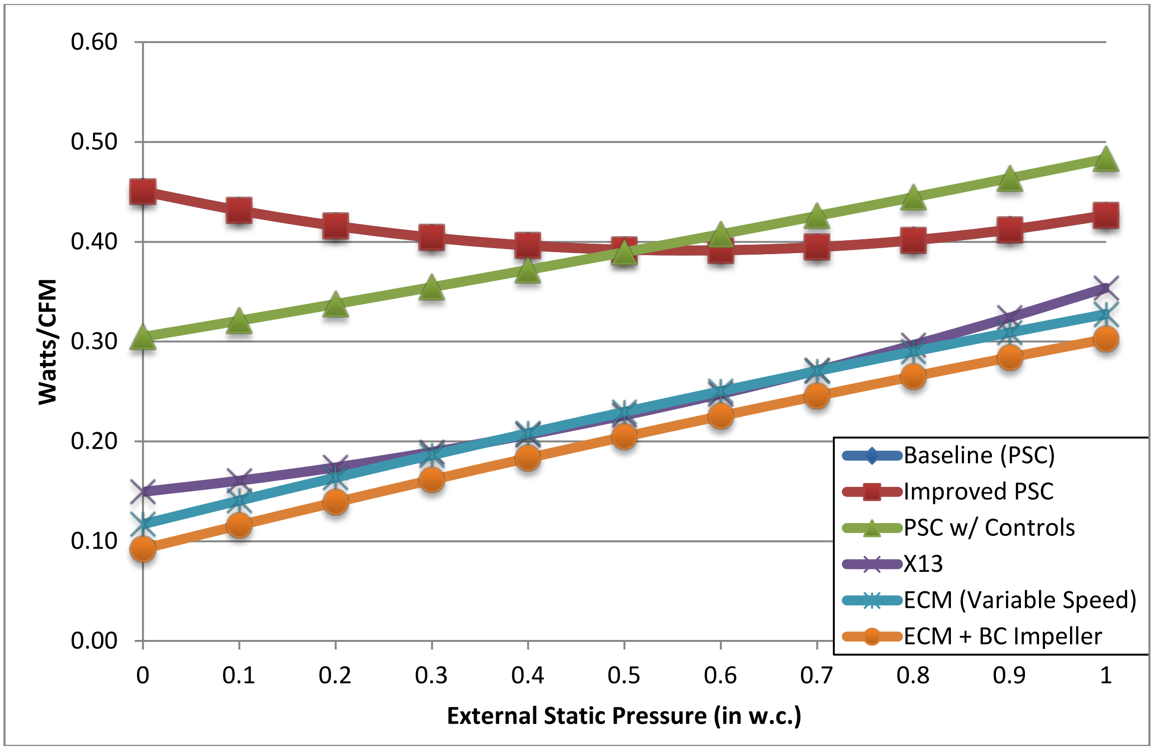

Figure 7-C.5.5 Watt/CFM Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Heating Mode)

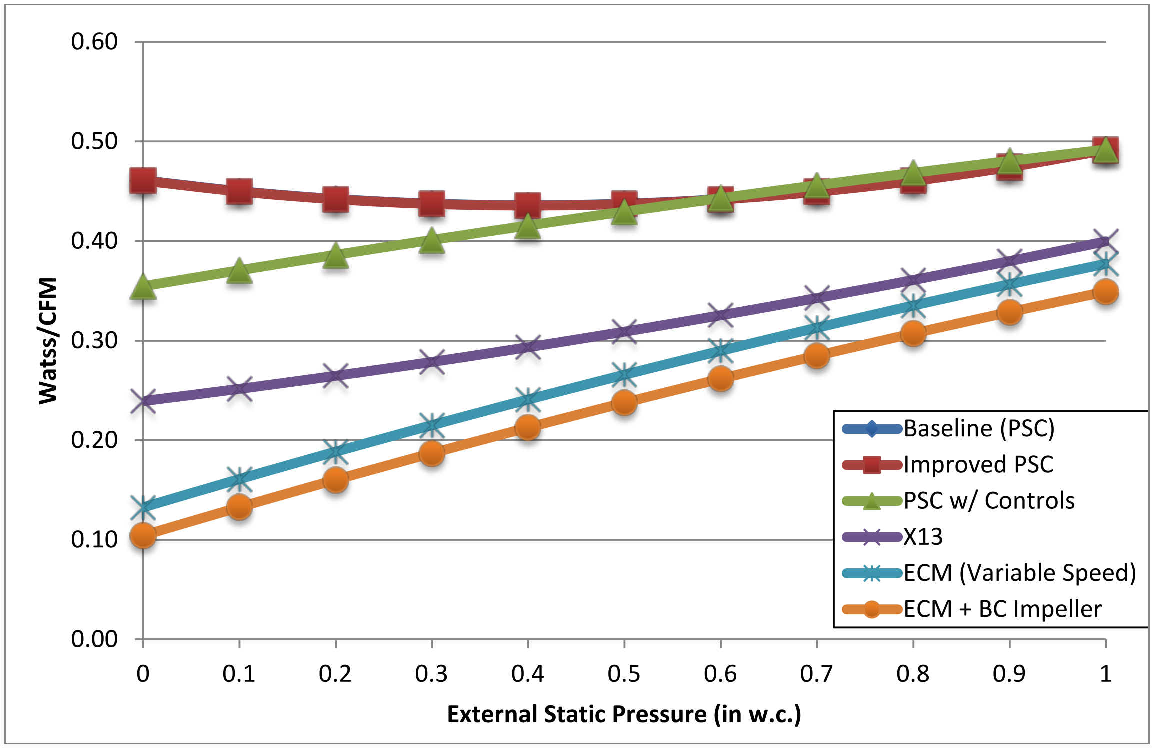

Figure 7-C.5.6 Watt/CFM Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Cooling Mode)

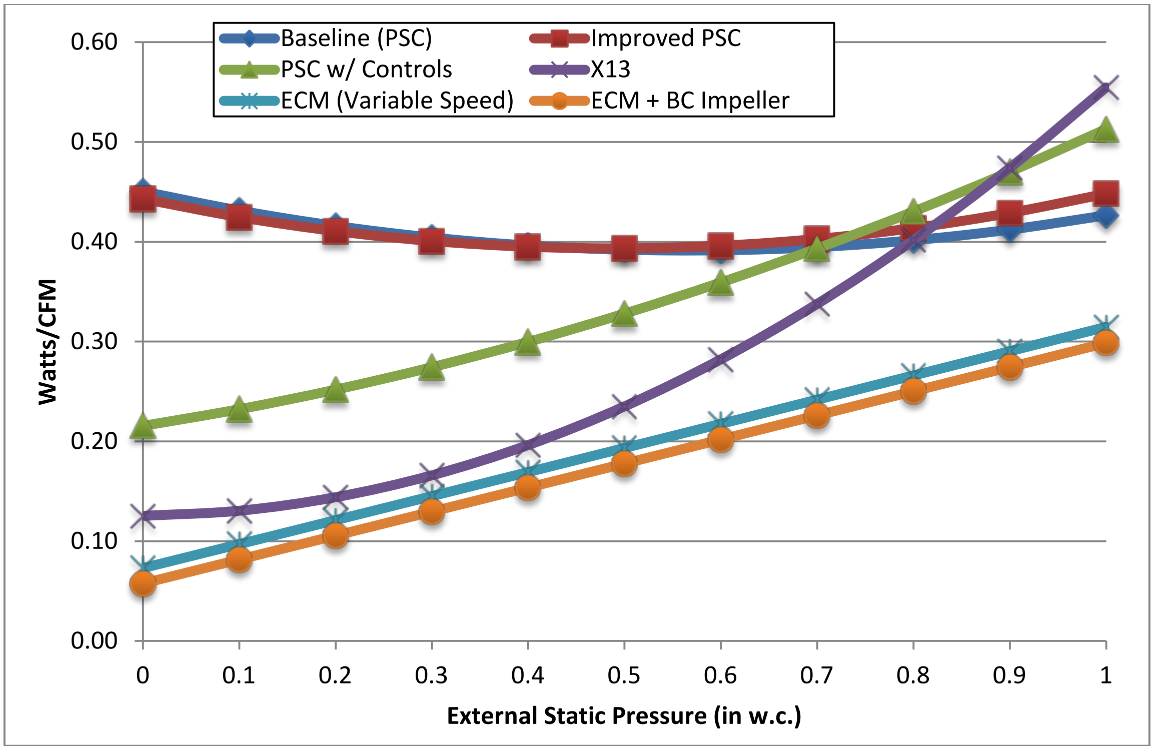

Figure 7-C.5.7 Watt/CFM Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Continuous Fan Mode)

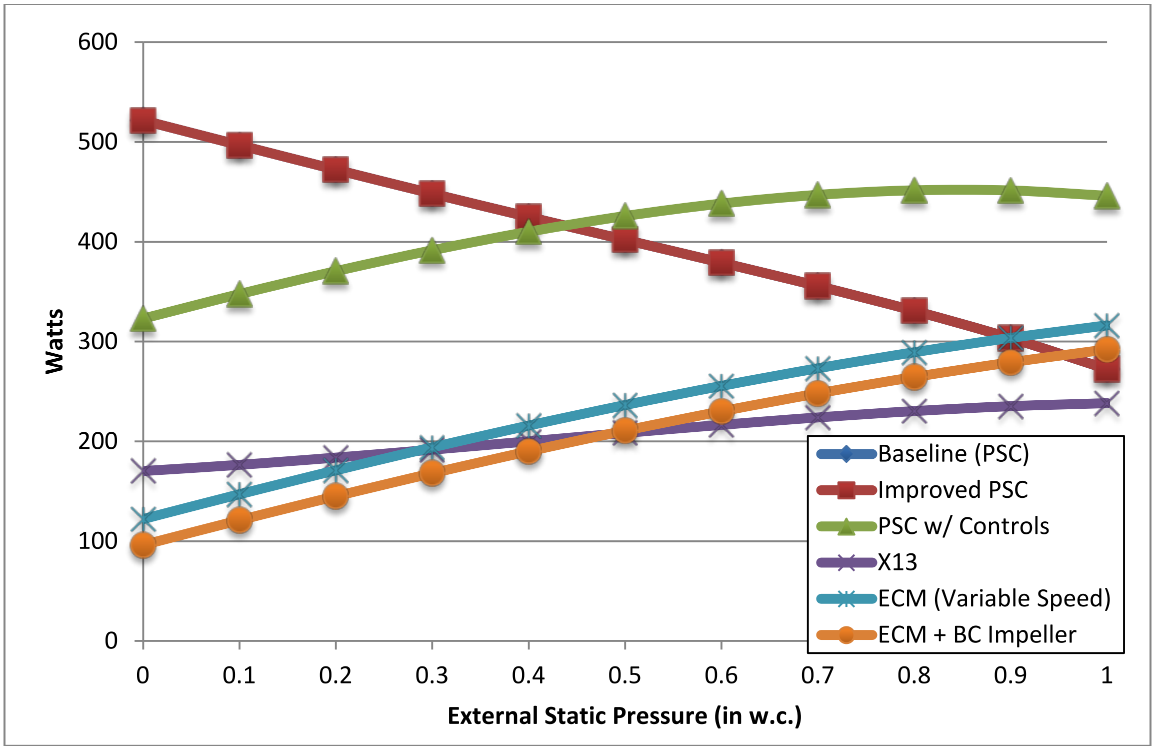

Figure 7-C.5.8 Resulting Watt vs. Pressure Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Heating Mode)

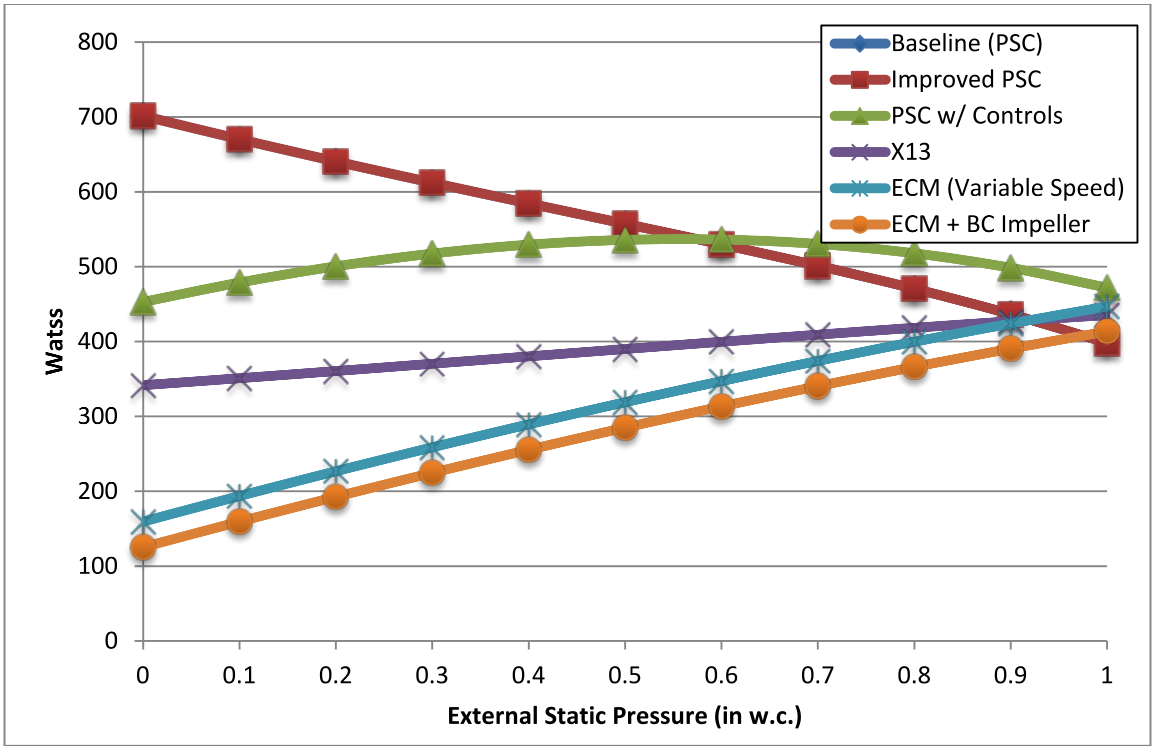

Figure 7-C.5.9 Resulting Watt vs. Pressure Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Cooling Mode)

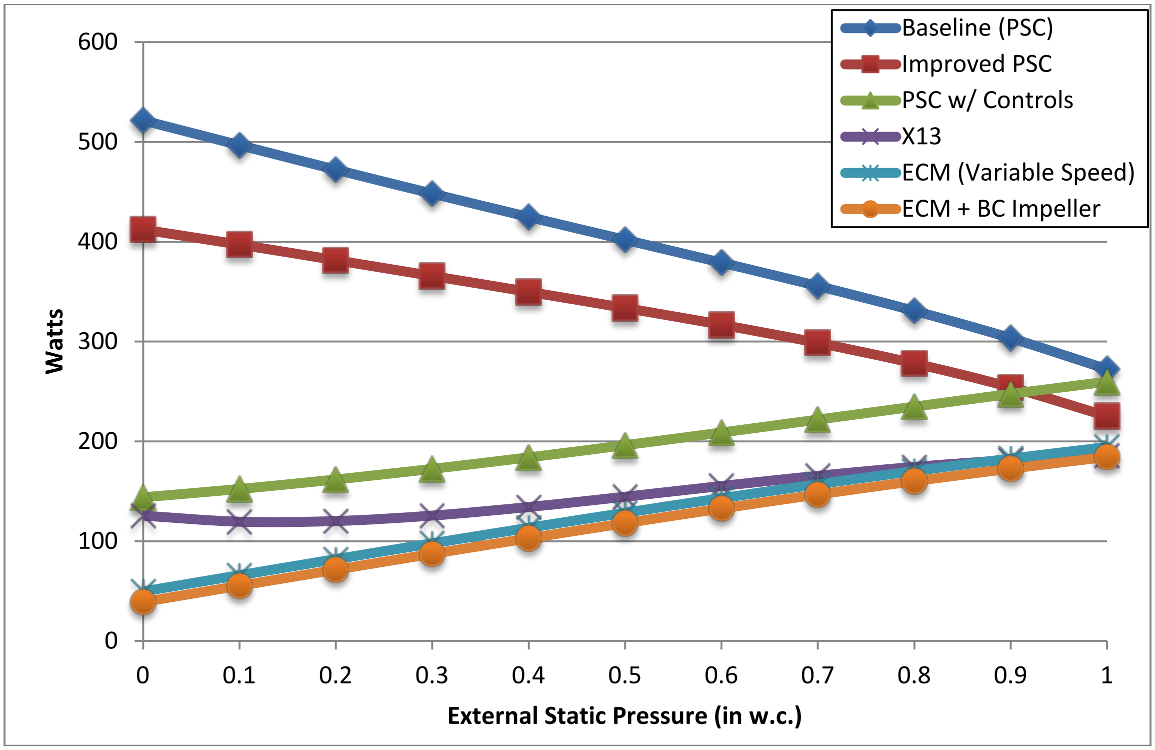

Figure 7-C.5.10 Resulting Watt vs. Pressure Curves for Non-Weatherized (Non-Condensing) Gas Furnace Fan, 3-Ton (Continuous Fan Mode)

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