CHAPTER 7. ENERGY CONSUMPTION OF FURNACES AND BOILERS

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CHAPTER 7. ENERGY CONSUMPTION OF FURNACES AND BOILERS

7.1 INTRODUCTION

The furnace and boiler energy-efficiency standards rulemaking considers the change in life-cycle cost (LCC) due to increased energy efficiency of household heating equipment. Energy consumption is the key part of the operating-cost input of the LCC calculation. The energy consumption of a furnace or boiler includes either gas or oil and electricity. In many cases, a furnace blower operates outside the heating season when the air handler is in use for cooling purposes, so DOE included this consumption in its calculations.

In the engineering analysis, the Department calculated energy consumption of baseline model-sized furnaces and boilers using the DOE test procedure for these types of equipment. For the LCC Analysis, DOE estimated energy consumption of furnaces and boilers in actual houses. To represent actual houses with furnaces and boilers in the United States, DOE used a set of houses from DOE's Energy Information Administration (EIA)'s Residential Energy Consumption Survey of 1997 (RECS97).[1] For each house, RECS97 reports space-heating energy consumption and space-cooling electricity consumption, which are based on the existing household equipment. The Department's method estimated the energy consumption of alternative (more-efficient) equipment, if they were used in each house in place of the existing equipment.

The Department developed the method of calculation described in this chapter for non-weatherized gas furnaces, the most common among the six product classes in the rulemaking analysis. The Department generalized the energy consumption calculation for this product class to the other furnace product classes. Fuel consumption calculations for boilers are similar to those for the furnace product classes. The electricity calculations for boilers are simpler than for furnaces, because boilers do not provide thermal distribution for space cooling as furnaces often do.

7.2 METHOD FOR NON-WEATHERIZED GAS FURNACES

To begin the analysis, the Department developed representative conceptual furnace models. These "virtual" models incorporated typical features of currently-marketed furnaces. The Department based the virtual furnaces on models selected from directories and product literature. The virtual models capture the range of actual furnace sizes. The analysis assigned an appropriate virtual furnace to each sample house as a way of modeling energy consumption of alternative furnace designs.

Estimating the annual energy consumption of alternative furnaces in each house required DOE to estimate the heating and cooling loads of each house. These loads represent the amount of heating and cooling required to keep a house comfortable during an entire year. The Department estimated the heating and cooling loads from the heating and cooling energy consumption and the assumed characteristics of the existing furnace and air conditioner in each sample house. The Department assigned the characteristics of the existing equipment to each sample house, depending on the size and climate zone of each house and the age of the heating equipment. The estimation of heating loads also required calculation of the electricity consumption of the furnace blower, since heat from the furnace blower contributes to heating the house.

To complete the analysis, the Department calculated how much energy would be required by furnaces with various design options to meet the same heating and cooling load of each sample house.

7.3 VIRTUAL FURNACE MODELS

To conduct the analysis, the Department developed conceptual furnace models. The Department intended these generic furnace models to represent typical furnaces with basic features, but not to describe specific, existing furnaces. The Department derived the characteristics of the virtual furnace models from existing "basic" furnace models, after examining directories and product literature of existing furnaces. See Appendix 7.1, Reduced Set of Furnace Models, Database for more details.

As a starting point for choosing values of input capacity for the virtual furnace models, the Department looked at the number of models listed by input capacity in the Gas Appliance Manufacturers Association (GAMA) Directory of April 2002[2] (see Figure 7.3.1). The Department selected models that were non-weatherized gas furnaces, that were not designed for mobile homes, and that were not discontinued. Using these selection criteria, DOE reduced the 36,032 gas furnace models in the GAMA Directory to 15,881 models. For virtual furnaces, DOE selected twelve input capacities that were the most common and that spanned the range on the market. The Department made these selections based on the assumption that the sizes that have the most models are the most popular.

The Department defined airflow capacity as the nominal maximum airflow at 0.5 inches water gauge (in.w.g.) external static pressure, as listed in the product literature for each model.[a] Manufacturers usually code this airflow capacity in the model number (see Appendix 7.2 on Decoding of Manufacturer Model Numbers, for more details.) Most of the furnaces fit into four airflow capacity sizes: 800 cubic feet per minute (cfm), 1200 cfm, 1600 cfm, and 2000 cfm. These airflow capacities correspond to nominal air-conditioner sizes of two tons, three tons, four tons, and five tons, respectively. The Department used the same set of airflow and capacity sizes for both non-condensing and condensing furnaces.

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[a] Furnaces are capable of providing several levels of airflow. For heating operation, a low level of airflow is used. If the furnace provides airflow for an air conditioner during cooling operation, it is typically set to provide a higher level of airflow when the air conditioner is operating.

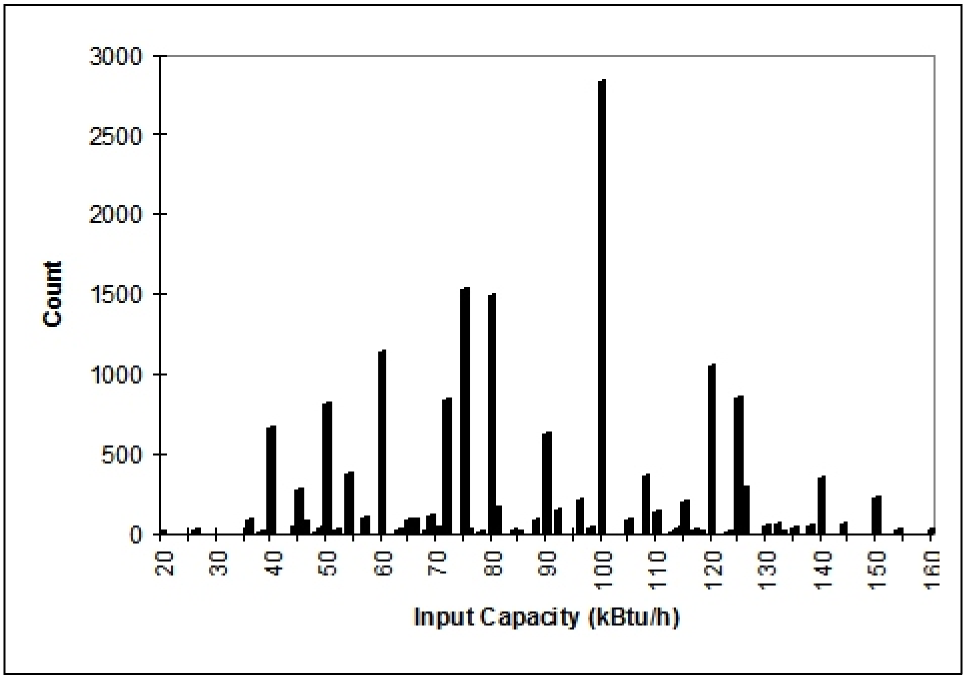

Figure 7.3.1 Number of GAMA Listed Furnace Models by Input Capacity

7.3.1 Basic Actual Furnace Models

The Department selected actual furnace models that represent the fundamental characteristics of non-condensing and condensing furnaces with no special features. The Department used the characteristics listed in Table 7.3.1 to select basic furnace models. These characteristics are the most common among models on the market (see Appendix 7.1, Reduced Set of Furnace Models Database). The Department selected several dozen furnace models that have these features. It looked in detail at these basic models to determine specific characteristics to use for creating virtual furnaces.

Table 7.3.1 Characteristics of Basic Furnace Models

Non-Condensing Gas Furnace	Condensing Gas Furnace
single stage burner	single stage
80% AFUE	90-92% AFUE
permanent split capacitor (PSC) blower motor	PSC blower motor
forward-curved impeller blades	forward-curved impeller blades
up-flow or horizontal air-flow	down-flow, up-flow, or horizontal air-flow

The basic furnace models are listed by brand and series in Appendix 7.3A, which contains basic non-condensing model data, and Appendix 7.3B, basic non-condensing model data.

7.3.2 Input Capacity and Maximum Airflow

7.3.2.1 Non-weatherized gas furnaces.

For virtual furnace models, DOE selected 25 combinations ("bins") of input capacity and maximum airflow. The marked cells in Table 7.3.2 reflect the input capacity and nominal maximum airflow for the virtual furnace models. The selection reflects the most common input and nominal maximum airflow capacities of models in the GAMA Directory April 2002,[3] in product literature, and listed on furnace manufacturer web sites. Most basic models on the market fit into the 25 bins of input capacity and airflow capacity. Some models do not exactly match the bins, but their values are close enough that DOE included them in one of the 25 bins. For example, 40 kBTU/h and 45 kBTU/h models are grouped together into a single 45 kBTU/h bin. Most bins have at least two actual models.

Table 7.3.2 Virtual Model Furnaces: Capacity and Airflow

		Input Capacity (kBTU/h)											
Maximum Airflow (at 0.5" Static Pressure)		45	50	60	70	75	80	90	100	115	120	125	140
	800 cfm (2 tons)	x	x	x									
	1200 cfm (3 tons)	x	x	x	x	x	x	x	x				
	1600 cfm (4 tons)				x	x	x	x	x	x	x	x	
	2000 cfm (5 tons)							x	x	x	x	x	x

The Department created one virtual model to represent all the models assigned to each bin. The Department used specifications from the actual models in each bin to determine the specifications for the corresponding virtual model. These specifications include blower size, motor size, supply-air outlet area, power consumption of the draft inducer and the igniter, and several delay times. The specifications are described in the sections below.

7.3.2.2 Other Product Classes.

Because of the limited number of sizes available for mobile home gas furnaces and oil-fired furnaces, DOE selected a subset of the 25 input and airflow capacity combinations to represent each product class. In its analysis of weatherized gas furnaces, DOE used the same virtual models as it used in the analysis of non-weatherized gas furnaces. For mobile home furnaces and oil-fired furnaces, the Department used a subset of the 25 virtual furnace models, because the market in those product classes is limited to a smaller number of sizes of furnaces. Tables 7.3.3-7.3.5 list the relevant sizes for non-weatherized and weatherized gas, mobile home, and oil-fired furnaces.

Table 7.3.3 Relevant Sizes of Virtual Models for Non-Weatherized and Weatherized Gas Furnaces

		Input Capacity (kBtu/h)											
		45	50	60	70	75	80	90	100	115	120	125	140
Max. Airflow (tons)	2	X	X	X									
	3	X	X	X	X	X	X	X	X				
	4				X	X	X	X	X	X	X	X	
	5							X	X	X	X	X	X

Table 7.3.4 Relevant Sizes of Virtual Models for Mobile Home Furnaces

		Input Capacity (kBtu/h))									
		60	70	75	80	90	100	115	120	125	140
Max. Airflow (tons)	2	X		X		X					
	3	X		X		X					
	4	X		X		X					
	5	X		X		X					

Table 7.3.5 Relevant Sizes of Virtual Models for Oil-Fired Furnaces

		Input Capacity (kBtu/h)											
		45	50	60	70	75	80	90	100	115	120	125	140
Max. Airflow (tons)	2												
	3				X			X	X				
	4								X		X		
	5								X		X		X

7.3.3 Blower Size

The Department selected a blower size (listed as nominal diameter in inches by nominal width in inches) for each virtual furnace model (Table 7.3.6). The blower size is typical for the basic furnace models in each bin. Blower size increases with airflow capacity, but not with input capacity. The Department used four blower sizes—the same ones for condensing and non-condensing virtual furnace models. For the blower sizes of basic furnace models, see Appendix 7.3, Determination of Basic Model Furnaces.

Table 7.3.6 Assigned Blower Size by Airflow Capacity

Airflow Capacity (cfm)	Blower Size (inches)
2-ton models (800 cfm)	9 X 8
3-ton models (1200 cfm)	10 X 8
4-ton models (1600 cfm)	10 X 10
5-ton models (2000 cfm)	11 X 10

7.3.4 Motor Size

The motors for the basic furnace models are six-pole permanent split capacitor (PSC) induction motors. The motors in the basic furnaces come with three to five taps that are used to set the motor speed. The Department assumed that, at high speed, the motors operate with a speed of 1075 revolutions per minute (rpm) to provide the nominal maximum airflow at 0.5 in.w.g.

The Department assigned motor size to virtual furnace models, as shown in Table 7.3.7, to reflect typical-size motors of the basic furnace models. Motor sizes are the same for non-condensing and condensing furnaces. The larger the nominal maximum airflow, the larger the motor size. For the blower motor size and number of taps on basic model furnaces, see Appendix 7.3, Determination of Basic Model Furnaces, which lists the blower-motor sizes and number of blower motor taps of basic furnace models.

Table 7.3.7 Assigned Motor Size by Airflow Capacity

Airflow Capacity (cfm)	Motor Size (HP)
2-ton models (800 cfm)	1/5
3-ton models (1200 cfm)	1/3
4-ton models (1600 cfm)	1/2
5-ton models (2000 cfm)	3/4

7.3.5 Supply-Air Outlet Area

The supply-air outlet area is the opening from the furnace to the supply duct. The supply-air outlet area for basic furnace models increases with airflow capacity and input capacity. To capture this trend, DOE constructed a linear fit of the supply-air outlet area to input capacity and airflow capacity for condensing and non-condensing furnaces (see Appendix 7.3, Determination of Basic Model Furnaces, for supply-air outlet areas of basic furnace models). The Department used the following equations to determine the supply-air outlet area of the non-condensing and condensing virtual model furnace models:

$$S = 0.7882 + 0.5006 \times (Q / 1000) + 0.0087 \times (Qin)$$

$$S = 0.9498 + 0.5505 \times (Q / 1000) + 0.0073 \times (Qin)$$

where:

S = supply-air outlet area (sq. ft.),;
Q = nominal maximum airflow (cfm) at 0.5 in.w.g. static pressure,; and
Qin = input capacity (kBtu/h).

Figures 7.3.2 and 7.3.3 show the data points for supply-air outlet area for basic furnace models and the linear plane fit used to fit these points.

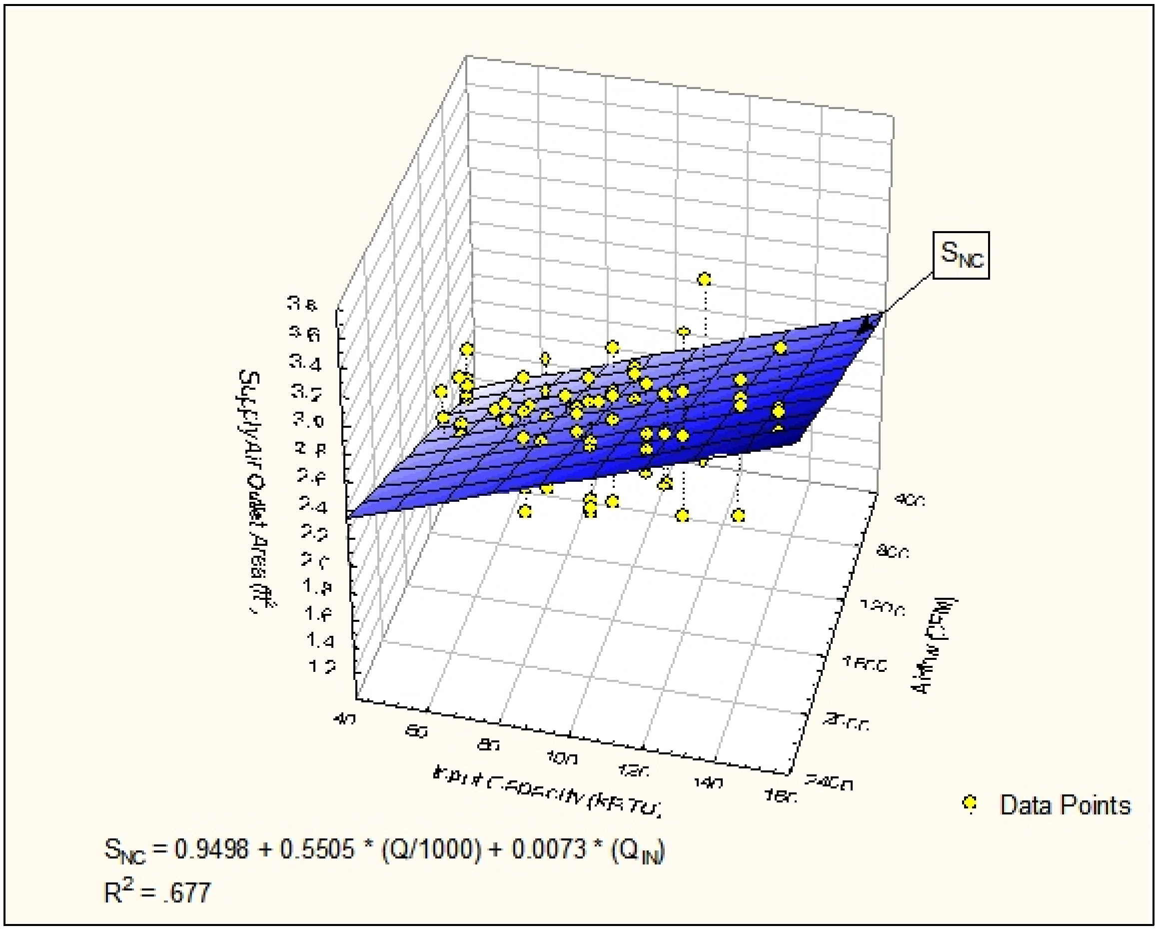

Figure 7.3.2 Supply-Air Outlet Area for Non-Condensing Natural Gas Furnaces

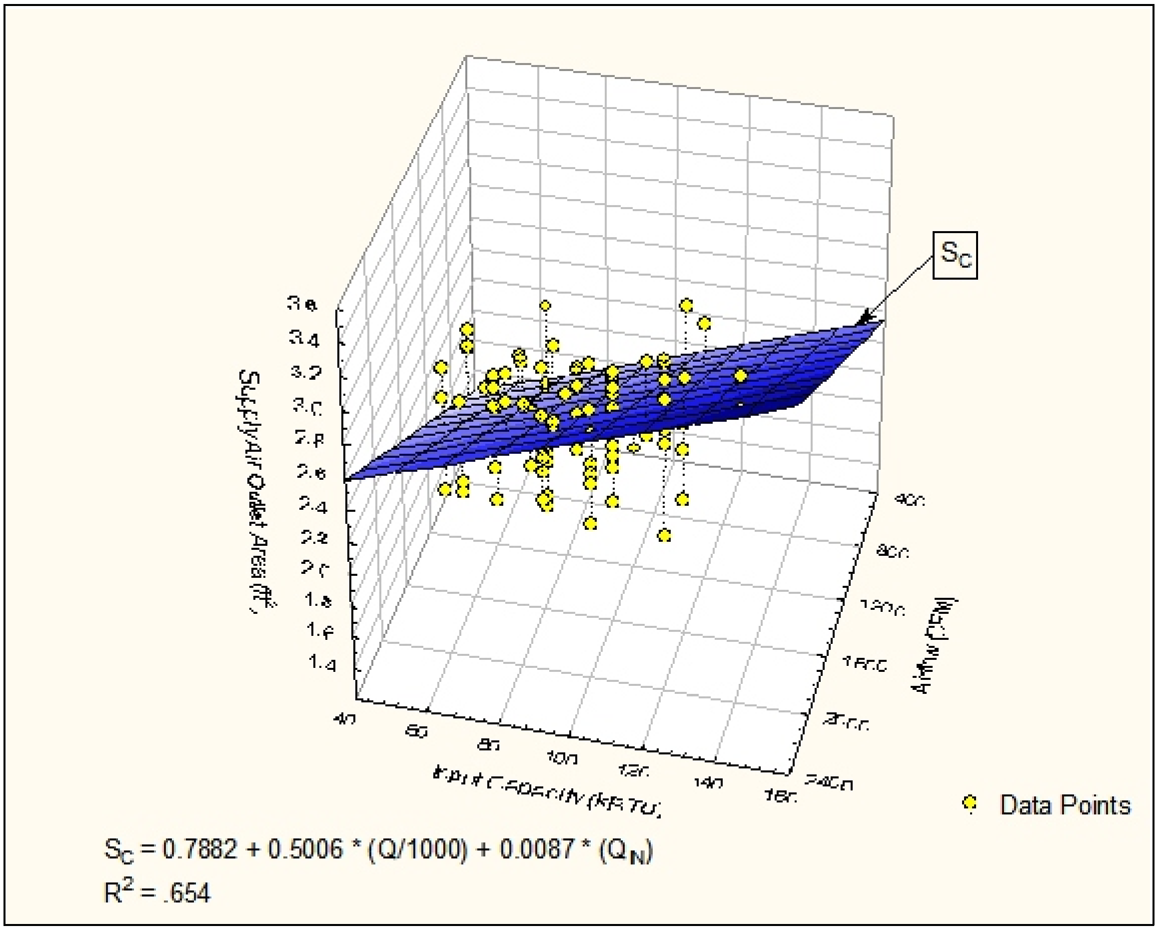

Figure 7.3.3 Supply-Air Outlet Area for Condensing Natural Gas Furnaces

Tables 7.3.8 and 7.3.9 show the values DOE used for supply-air outlet areas for non-condensing and condensing virtual gas furnaces.

The supply-air outlet area is larger for condensing models. The larger opening compensates for the increased pressure drop due to the secondary, condensing heat exchanger. This larger supply-air outlet area reduces the pressure drop across the furnace, so that the pressure rise for condensing furnaces is the same as non-condensing model furnaces at the same airflow.

Table 7.3.8 Supply-Air Outlet Area (in Square Feet) for Virtual Non-Condensing Gas Furnace Models

Maximum Airflow (at 0.5" Static Pressure)	Input Capacity (kBTU/h)											
	45	50	60	70	75	80	90	100	115	120	125	140
800 cfm (2 tons)	1.58	1.62	1.71									
1200 cfm (3 tons)	1.78	1.82	1.91	2.00	2.04	2.08	2.17	2.26				
1600 cfm (4 tons)				2.20	2.24	2.29	2.37	2.46	2.59	2.63	2.68	
2000 cfm (5 tons)							2.57	2.66	2.79	2.83	2.88	3.01

Table 7.3.9 Supply-Air Outlet Area (in Square Feet) for Virtual Condensing Gas Furnace Models

Maximum Airflow (at 0.5" Static Pressure)	Input Capacity (kBTU/h)											
	45	50	60	70	75	80	90	100	115	120	125	140
800 cfm (2 tons)	1.72	1.76	1.83									
1200 cfm (3 tons)	1.94	1.98	2.05	2.13	2.16	2.20	2.27	2.35				
1600 cfm (4 tons)				2.35	2.39	2.42	2.50	2.57	2.68	2.72	2.75	
2000 cfm (5 tons)							2.06	2.79	2.90	2.94	2.97	3.08

7.3.6 Power Consumption of Draft Inducer

A common value for the power consumption of the draft inducer, PE, for basic non-condensing model furnaces is 75 watts, and the average value is about 75 W, so DOE selected 75 W for all the non-condensing models. The Department found no correlation between the PE and input capacity or between PE and airflow capacity. For condensing furnaces, the Department used a PE of 90 W, which closely matches the mean for that group. See Appendix 7.3, Determination of Basic Model Furnaces, for the power consumption of the draft inducer in the basic models.

7.3.7 Delay Times and Ignitor Power

Pre-purge and post-purge times are the lengths of time the draft inducer operates before and after a firing cycle. On-delay is the amount of time the blower waits to begin operating after the burner starts firing. Off-delay is the time the blower keeps operating after the burner turns off. Ignition time is the length of time the hot surface ignitor is on before gas is sent to the burner.

Pre-purge, post-purge, on-delay, and off-delay times are not related to airflow or input capacity. The Department selected common values for the delay and ignition times of condensing and non-condensing virtual furnace models (Table 7.3.10). For these data on basic furnace models, see Appendix 7.3, Determination of Basic Model Furnaces.

Table 7.3.10 Values for Delay and Ignition Times

Pre-Purge	Post-Purge	On-Delay	Off-Delay	Ignition
15 seconds	5 seconds	30 seconds	120 seconds	37 seconds

7.4 ASSIGNING EXISTING EQUIPMENT TO SAMPLE HOUSES

To estimate the heating and cooling load of each sample house, DOE assigned the input capacity, airflow capacity, annual fuel utilization efficiency (AFUE), and for the air conditioner (if the house has one), the seasonal energy-eficiency ratio (SEER). As part of the heating- and cooling-load calculations, DOE estimated the electricity consumption and efficiency of the furnace blower motor. The Department used the input capacity and nominal maximum airflow capacity assigned to the existing furnace to choose the virtual furnace model for the house, for use in the rest of the LCC analysis.

7.4.1 Furnace Input Capacity

The Department assigned an input capacity for the existing furnace of each house based on an algorithm that correlates input capacity with the house size, the year the furnace was installed, and the distribution of input capacity of new furnaces sold the year the furnace was installed. The following steps describe the assignment process.

(1) The Department ranked all the RECS97 houses in ascending order by size (square foot) and calculated the percentile rank of each house using the statistical weight of each of the sample records.

(2) The Department constructed percentile tables by input capacity of furnaces sold each year for 1997 and prior years, based on the historical shipment information for each year.[4]

(3) After selecting a house from the RECS97 database during each Monte Carlo iteration, DOE noted the size of the selected house and determined the percentile rank from Step 1.

(4) To avoid a one-to-one deterministic relation between the house size and input capacity, DOE added a random term to the percentile identified in Step 3 so that the correlation was not perfect. The Department used a normal distribution to characterize the random term. The random term has a mean of zero and a standard deviation of 8 percent.

(5) Using the percentile from Step 4, DOE looked up the input capacity from the input capacity percentile table in Step 2 for the age of the equipment.

(6) Figure 7.4.1 shows the percent of existing furnaces by input capacity assigned to the sample houses.

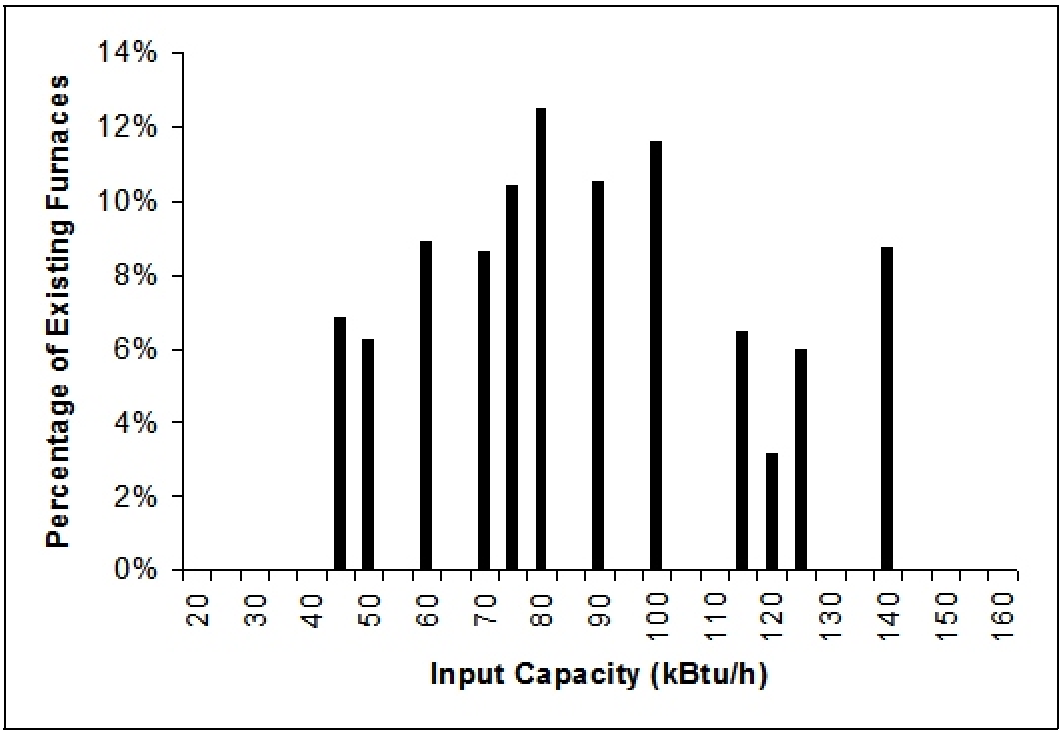

Figure 7.4.1 Percent of Existing Furnaces by Input Capacity

7.4.2 Airflow Capacity

The Department classified furnaces by nominal maximum airflow in cfm at 0.5 in.w.g. of external static pressure. The Department assigned the airflow capacity of existing furnaces for houses that had air conditioners in a similar manner that it assigned furnace input capacity. Larger air conditioners go to larger houses, according to the distribution of sizes of air conditioners sold the year the air conditioner was installed in that house. The Department used the air conditioner nominal size of two, three, four, or five tons to set the airflow capacity with a ratio of 400 cfm per ton of cooling. The steps were:

(1) Based on the historical shipment information of residential central air conditioners by capacity, DOE constructed the airflow capacity percentiles tables for air conditioners sold in 1997 and prior years. The Department restricted the airflow sizes to two, three, four, or five tons—the equivalent of 800, 1200, 1600, or 2000 cfm at 0.5 in.w.g. static pressure. The variation of the distribution of the four airflow sizes over the years is small. Most of the annual sales of residential central air conditioners from 1976 to 1994 are in these airflow sizes.
(2) Since there are no available shipment data on the airflow capacity of furnaces, the Department used the airflow capacity of residential central air conditioners as a proxy. Using the adjusted percentile of house size from Step (4) in the Input Capacity section, DOE determined the airflow capacity by looking up the percentile in the corresponding distribution of nominal air conditioner size for the age of the cooling equipment. The Department selected a virtual model with the identified airflow capacity. If no virtual model with the identified airflow capacity was available, the Department selected the virtual model with the same input capacity and the closest airflow capacity as a substitute.
(3) If the RECS record indicated that the house did not have an air conditioner, DOE still used the procedure from step (2) to determine the airflow capacity. In this case, DOE used the age of the house (or 30 years if the house was older than 30 years) as a substitute for the age of the cooling equipment.

7.4.3 Efficiency Characteristics of Existing Equipment

GAMA shipments data indicate that houses in colder regions receive more-efficient furnaces.[4] Therefore, DOE correlated the AFUE of existing furnaces with the heating degree days (HDD) to base 65°F associated with each sample house. The following steps describe this process:

(1) The Department sorted the RECS houses in ascending order of HDDs, and calculated the percentile rank of each house by HDD using the statistical weight of each sample house.
(2) Based on the historical furnace shipment information sorted by AFUE, DOE constructed percentile tables by AFUE shipments of furnaces for 1997 and prior years.
(3) After DOE selected a house from the RECS database during each Monte Carlo iteration, it noted the HDD of the selected house. The Department looked up the percentile rank of that house from the HDD percentile table developed in Step (1).
(4) The Department added a random uncertainty term to the HDD percentile found in Step (3) to account for variability within the sample. The Department used a normal distribution to characterize the uncertainty term. The distribution of values of the uncertainty term has a mean of zero and a standard deviation of 8 percent.

(5) Using the adjusted HDD percentile from Step (4), DOE determined the AFUE by looking it up from the AFUE percentile table from Step (2) corresponding to the age of the existing equipment in the house.

Houses with central air conditioners use the circulating-air blower in the furnace to circulate the conditioned air during the cooling season. If a house had an air conditioner, DOE assigned it a SEER level. Unlike AFUE, SEER was not correlated with any other housing factors. The Department constructed SEER distributions for all years from historical shipment data; it randomly selected a SEER from the distribution for the year of the age of equipment in each house.

7.4.4 Electricity Consumption of the Existing Furnace Blower

All furnaces manufactured since about 1980 use forward-curved impellers driven directly by a PSC motor. Thus, most existing furnaces have a blower and blower motor similar to those in the virtual furnace models.[b] Therefore, in assigning the electricity consumption of the existing furnace blower for each house, DOE assumed that the electricity use of the existing furnace was equivalent to the electricity use of the virtual furnace model described in section 7.2.

The Department calculated electricity use by the existing furnace from the fan curves, overall efficiency, airpower, and time delays of the virtual furnace model of the same input capacity and airflow capacity.

7.5 CALCULATING FURNACE BLOWER ELECTRICITY CONSUMPTION

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 house will operate. These operating conditions can be graphically displayed as the intersection of a system curve of the ducts in the house (which plots the static pressure across the supply and return air ducts as a function of airflow) with the fan curve of the furnace (which plots the static pressure across the furnace as a function of airflow). The intersection of these two curves is the static pressure and the airflow at which the furnace will operate in that house.

Furnace fan curves, reported as tables of static pressure rise versus airflow through the furnace, are available from manufacturers in the product literature for each furnace. One of the

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[b] A very small share of existing furnaces use belt-drive blowers with shaded-pole motors. That arrangement was less efficient than direct-driven PSC motors, but the airflow from these old model furnaces was less, so electricity consumption was not significantly reduced when this technology became obsolete.[5]

manufacturers also supplies blower-motor input power as a function of airflow through 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.

7.5.1 System Curves

The system curve of the air-distribution system is a graphical representation of the static pressure drop generated across the supply and return ducts in a house for different airflows. 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.[4]

The Department modeled system curves as quadratic curves, which is standard in heating, ventilation, and air conditioning (HVAC) design and fan selection handbooks.[6] The curves are based on Bernoulli's equations for fluid flow and are expressed as the following equation:

$$P = \alpha \times Q^2$$

where:

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

The Department selected the coefficient in the system curve equation for each house. It randomly sampled a coefficient from one of four distributions, depending on the nominal maximum airflow of the virtual model furnace selected for that house. 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.[7] 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 7.5.1 for an example of a plot of system curves intersecting a furnace fan curve.

7.5.2 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 pressure values are plotted graphically against airflow, they are referred to as fan curves.

The Department assigned three fan curves to each virtual furnace model: one for cooling operation, one for heating, and a third for the low-fire heating operation of modulating design options. In cooling operation, the fan curve passes through the nominal maximum airflow at 0.5 in.w.g. external static pressure. During normal heating operation, airflow is 80 percent of the nominal maximum airflow at 0.5 in.w.g. external static pressure. The airflow for low-fire heating operation at 0.5 in.w.g. static pressure is 2/3 of the nominal maximum airflow at the same external static pressure.

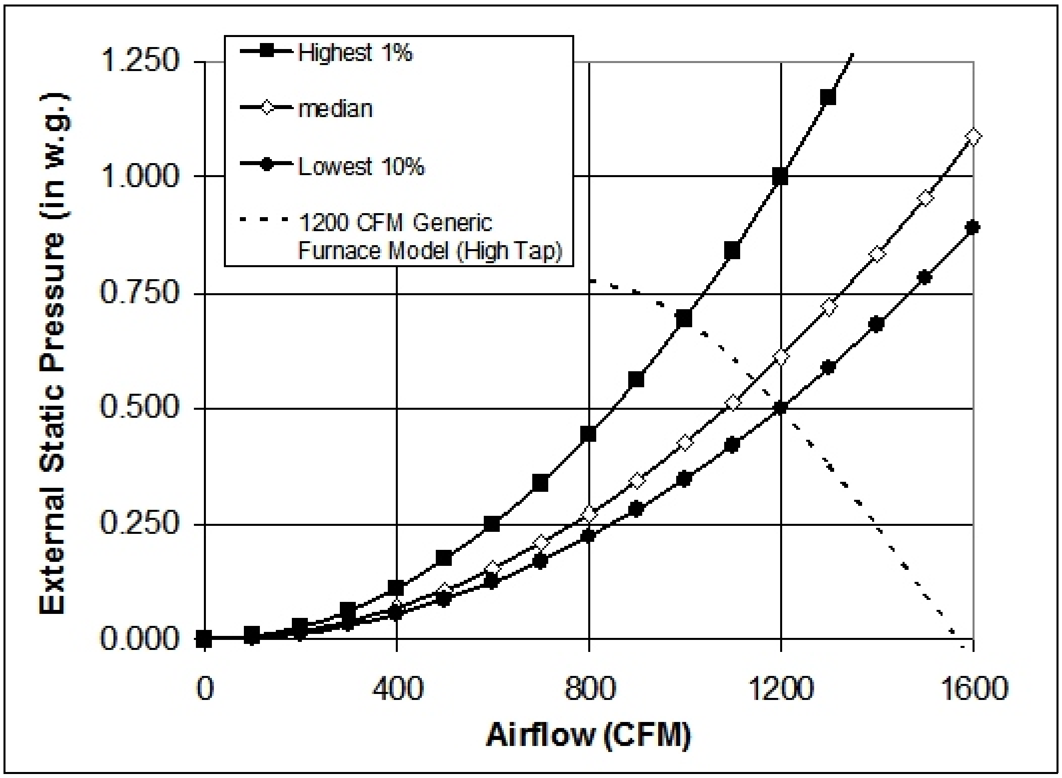

Figure 7.5.1 Sample of System Curves with a Typical Fan Curve

The Department developed fan curves for the virtual furnace models as detailed in Appendix 7.4, Furnace Fan Curves. Figures 7.5.2–7.5.5 show the fan curves for that virtual furnace models. From the left, the line closest to vertical axis shows a fan curve for that virtual furnace model operating in low-fire mode, the middle line is for the virtual furnace model operating in heating mode, and the line furthest to the right, which passes through 0.5 in. w.g. static pressure at the nominal maximum of airflow, is the fan curve for the virtual furnace models operating in cooling mode.

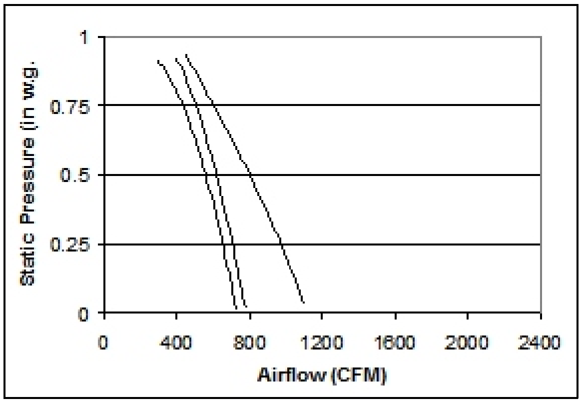

Figure 7.5.2 Fan Curves for 800 cfm Virtual Furnace Model

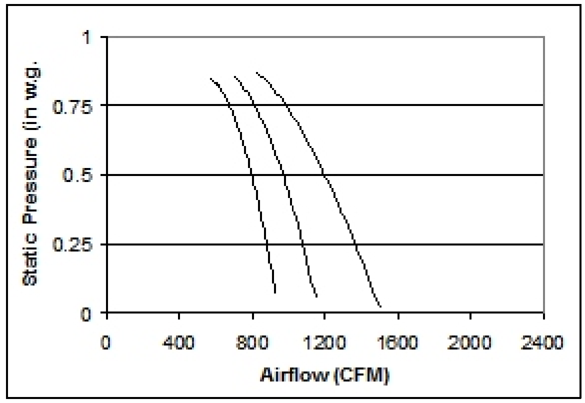

Figure 7.5.3 Fan Curves for 1200 cfm Virtual Furnace Model

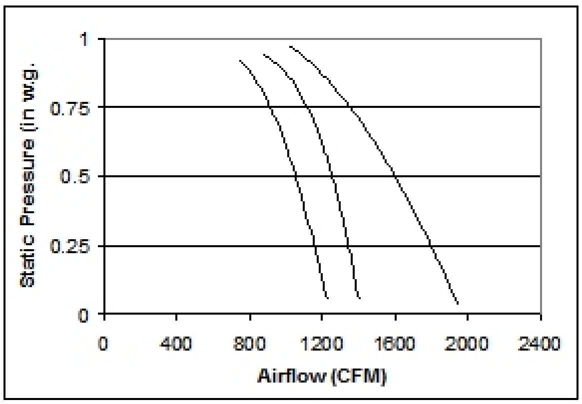

Figure 7.5.4 Fan Curves for 1600 cfm Virtual Furnace Model

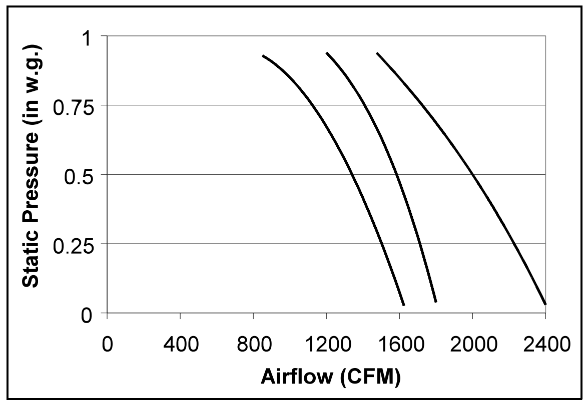

Figure 7.5.5 Fan Curves for 2000 cfm Virtual Furnace Model

7.5.3 Overall Air-Moving Efficiency

The overall air-moving efficiency is the air power divided by the electric power used by the blower motor.

Air power (air horsepower, or AHP), the power added to the air because of its motion and pressure increase as it is forced through the furnace, is calculated as:[8]

$$AHP = \left(\frac{745.7}{6356}\right) \times Q \times \left[P + \left(\frac{Q}{4005 \times A}\right)^2\right]$$

where:

AP	=	air power (watts),
Q	=	airflow (cfm),
$\frac{745.7}{6356}$	=	a conversion factor to express air horsepower in watts,
4005	=	a conversion factor to express the velocity pressure of standard air in w.g.,[c]
P	=	external static pressure (in.w.g.), and
A	=	cross-sectional airflow area defined as the supply-air outlet area (sq.ft.).

In addition to airflow at a range of external static pressures, one manufacturer reports fan motor electricity consumption.[9, 10, 11, 12, 13, 14] This allowed DOE to calculate the overall efficiency from data in that manufacturers' product literature.

$$\eta_{overall} = \frac{AP}{BE}$$

where:

$\eta_{overall}$	=	overall air moving efficiency,
BE	=	fan motor electricity consumption (W), and
AP	=	air power (W).

The Department calculated air power and overall efficiency for each point in the fan operating tables for each of the models. To generalize this relation of overall air-moving efficiency to airflow, the Department transformed airflows to percentages of airflow at free flow for all the furnaces. The Department did this calculation separately for condensing and non-condensing furnaces. The transformation of airflow to fraction-of-airflow-at-free-flow allowed DOE to plot all of the curves of overall air-moving efficiency together (as an example of the transformed data, see Figures 7.5.6–7.5.8).

The Department fit these curves to a single equation of overall efficiency as a function of the ratio of airflow to free airflow as follows:

$$\eta_{overall} = c0 + c1 \times (1 - Q_0) + c2 \times (1 - Q_0)^{(1/2)} + c3 \times (1 - Q_0)^{(1/3)}$$

where:

---

[c] The velocity pressure is the increase in pressure caused by the motion of air.

$\eta_{overall}$	=	overall air moving efficiency;
Q_0	=	ratio of airflow to free flow, and
c_0, c_1, c_2, c_3	=	empirically determined coefficients.

Figures 7.5.7 and 5.7.8 show the curve fit for high-fire heating and low-fire heating, and cooling for non-condensing and condensing furnaces.

For details of the overall air-moving efficiency and tables of coefficients for each of the virtual furnaces and operating modes, see Appendix 7.6, Overall Air-Moving Efficiency.

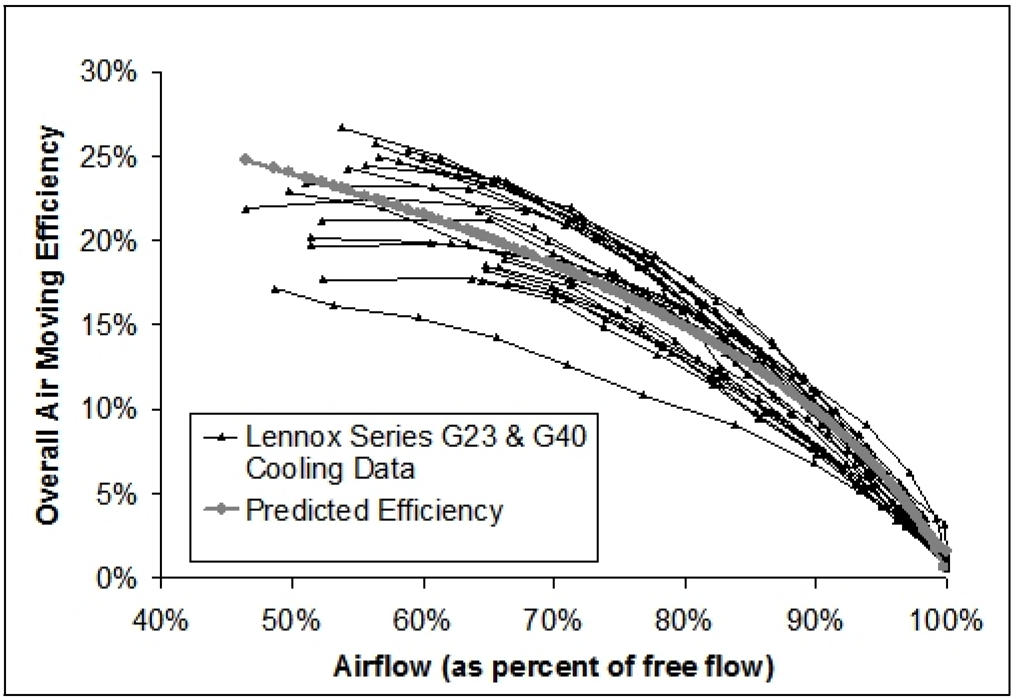

Figure 7.5.6 Overall Air-Moving Efficiency of Existing Furnaces

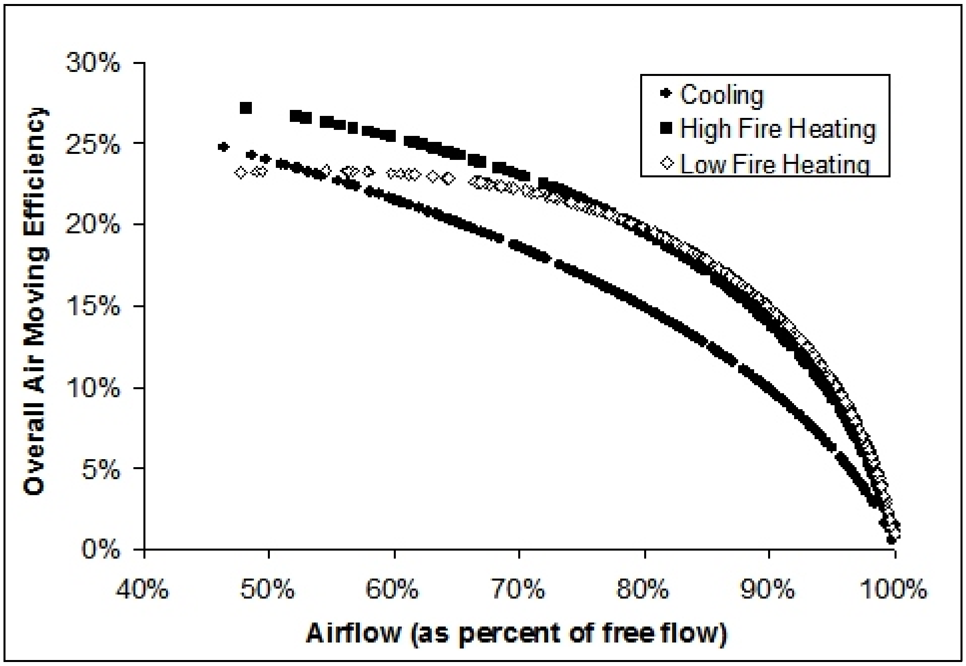

Figure 7.5.7 Overall Air-Moving Efficiency of Non-Condensing Virtual Furnace Models

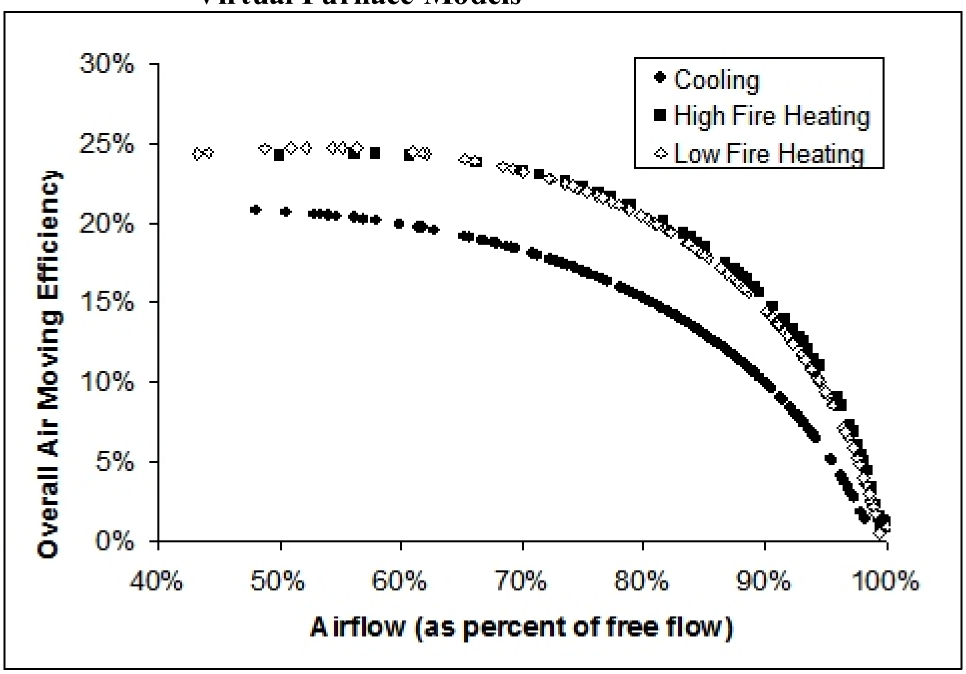

Figure 7.5.8 Overall Air-Moving Efficiency of Condensing Virtual Furnace Models

7.5.4 Blower-Motor Electricity Consumption

The circulating-air blower-motor electricity consumption in steady-state at full load is a function of airflow (*Q*), external static pressure (*P*), and the overall air-moving efficiency of the furnace ($\eta_{overall}$).

For a baseline model furnace, the Department calculated the circulating-air fan-motor electricity consumption for the forward-curved impeller with a direct-drive PSC motor as the air power divided by the overall air-moving efficiency of the blower and blower motor:

$$BE = \frac{AHP}{\eta_{overall}}$$

where:

BE	=	blower motor electricity consumption (W),
AP	=	air power (W), and
$\eta_{overall}$	=	overall air moving efficiency.

7.6 ANNUAL HEATING AND COOLING LOADS IN SAMPLE HOUSES

7.6.1 Annual House-Heating Load

The annual house-heating load (HHL) is the total amount of heat output from the furnace that the house needs during the heating season. This includes heat from the burner and heat from the blower and the blower motor.

Burner operating hours (BOH), the number of hours the furnace burner is on during a year, is a key variable in the calculation of HHL. The Department calculated BOH for the existing furnace as:

$$BOH = \frac{Q_{yr}}{Q_{in}}$$

where:

BOH	=	burner operating hours (hrs/yr),
Q_{yr}	=	annual fuel consumption for heating the house; from RECS97 (kBtu/yr), and
Q_{in}	=	input capacity of the existing furnace (kBtu/hr).

The Department determined HHL for each sampled household, based on the BOH and the characteristics of the assigned existing furnace, using the following calculations:

$$HHL = \left[Qin \times AFUEex + 3.412 \times y \times BE\right] \times BOH$$

where:

Q_{in}	=	input capacity of existing furnace (kBTU/hr),
$AFUE_{ex}$	=	AFUE of existing furnace,
3.412	=	constant to convert kW to kBTU/hr,
y	=	ratio of blower on-time to burner on-time in the heating mode (from DOE test procedure), and
BE	=	power consumption of the blower motor (kW).

The power consumption of the blower motor depends on the steady-state operating conditions (the pressure and airflow) for the furnace. This calculation is explained in section 7.5, Calculating Furnace Blower Electricity Consumption.

7.6.2 Annual House-Cooling Load

The annual house-cooling load (HCL) is the total amount of cooling provided to the house for the entire cooling season. It includes the cooling provided by the existing air conditioner, and accounts for the heat from the blower and blower motor. The Department calculated HCL from the cooling energy consumption reported in RECS97 and the SEER of the assigned existing air conditioners:

$$HCL = Q_{cool} \times SEER_{ex}$$

where:

HCL	=	annual house-cooling load (kBtu/h/yr),
Q_{cool}	=	annual house-cooling electricity consumption, from RECS97 kWh/yr), and
$SEER_{ex}$	=	SEER of the existing air conditioner (kBtu/h/kW).

7.7 FURNACE ENERGY CONSUMPTION

Once the heating and cooling loads of each sample house are known, it is possible to estimate what the energy consumption of alternative (more-efficient) furnaces would be if more-efficient furnaces, rather than the existing equipment, were used in each house.

7.7.1 Fuel Consumption

For each design option, BOH is different, since the AFUE and blower-motor electricity consumption are different. Therefore, each design option requires a different operating time to heat the same house. The Department calculated BOH as:

$$BOH = \frac{HHL}{Qin \times AFUE + 3.412 \times y \times BE}$$

where:

Q_{in}	=	input capacity of existing furnace (kBTU/h);
$AFUE$	=	AFUE of design option or efficiency level being considered;
3.412	=	a constant to convert kW to kBTU/h;
y	=	the ratio of blower on-time to burner on-time (heating mode); and
BE	=	the power consumption of the blower motor (kW).

The *BE* varies with airflow and static pressure, which are determined by the intersection of the furnace fan curve and the duct system curve.

The Department calculated the furnace fuel consumption for each design option and efficiency level using the following formula:

$$Fuel\_Use = BOHxQin$$

where:

BOH	=	burner operating hours (h), and
Q_{in}	=	input capacity of existing furnace (kBTU/h).

7.7.2 Electricity Consumption

The Department calculated furnace electricity consumption for the blower, the draft inducer, and the igniter.[d] The blower moves heated air through the house whenever the furnace burner is on (and the heat exchanger has reached a certain set-point temperature). It also operates in the cooling season (summer) if the house is air-conditioned. The electricity use calculation was carried out separately for winter and summer. The Department calculated the winter electricity consumption as:

$$ElecWinUse = BOH \times \left(y \times BE + y_P \times PE + y_{IG} \times PE_{IG}\right)$$

where:

BOH	=	burner operating hours (h),
y	=	ratio of blower on-time to burner on-time,
BE	=	power consumption of the blower motor (kW),
y_P	=	ratio of induced-draft blower on-time to burner on-time,
PE	=	power consumption of the draft-inducer blower-motor (kW),
y_{IG}	=	ratio of ignitor on-time to burner on-time, and
PE_{IG}	=	power consumption of the ignitor (kW).

The ratio of blower on-time to burner on-time and the ratio of induced draft blower on-time to burner on-time are from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) test procedure[15] using delay times for the virtual model furnaces. The ratio of ignitor on-time to burner on-time comes from the DOE test procedure[16] and the ignition time of the virtual model furnaces.[e]

Summer electricity use is due to the furnace circulating-air blower that moves the air cooled by the air conditioner. During cooling mode, the blower motor will operate at a high speed, so the airflow and static pressure conditions will be different from the heating mode conditions. The Department calculated summer electricity use as:

$$ElecSumUse = ACOHexisting \times BEcool$$

where:

$ACOHexisting$	=	air-conditioner operating hours (h/yr), and
BE_{cool}	=	power consumption of the blower-motor in cooling mode (kW).

[d] The DOE and ASHRAE test procedures do not count the electricity used by controls when the furnace is not firing.

[e] The ASHRAE test procedure does not deal with ignitor energy consumption.

The details for calculating energy consumption of modulating furnaces appear in Appendix 7.7, Gas and Electricity Use for Modulating Furnaces.

7.8 BOILER ENERGY CONSUMPTION

To assign the input capacity for the energy consumption calculation for hot-water gas and oil boilers, the Department used the input capacities of the virtual model furnaces for boilers, weighted according to the shipment data from GAMA.[3] The Department calculated the heating load for the house and the energy consumption of different model designs in a similar manner for furnaces. The power consumption of the circulating pump motor is 62 watts for the baseline model design.[17]

7.9 RESULTS

This section presents annual gas or oil consumption and winter electricity consumption for selected design options in each product class.

7.9.1 Non-Weatherized Gas Furnace Energy Use

The average annual household energy use for each design option for non-weatherized gas furnaces is shown in Table 7.9.1. The range of annual gas use for each design option is shown in Figure 7.9.1. Figure 7.9.2 shows the range of gas use for the 90 percent AFUE condensing furnace across the different regions of the country. Figure 7.9.3 shows the range of winter electricity consumption.

Table 7.9.1 Non-Weatherized Gas Furnace Energy Use

Design Option	Average Annual Gas Use (MMBtu)	Average Winter Electricity Use* (kWh)
78%	66.5	487
80%	64.9	476
80% 2-stage Mod.	63.5	492
81%, 8% Cat. III	64.1	470
81% 2-stage Mod, no Cat. III	62.8	487
82%	63.3	464
82% 2-stage Mod	62.0	481
83%	62.6	459
90%	57.9	421
92% Incr. HX Area	56.6	412
96% Step Mod ECM	54.0	226

* The average summer electricity use (for the blower) is 156 kWh for all of the design options shown.

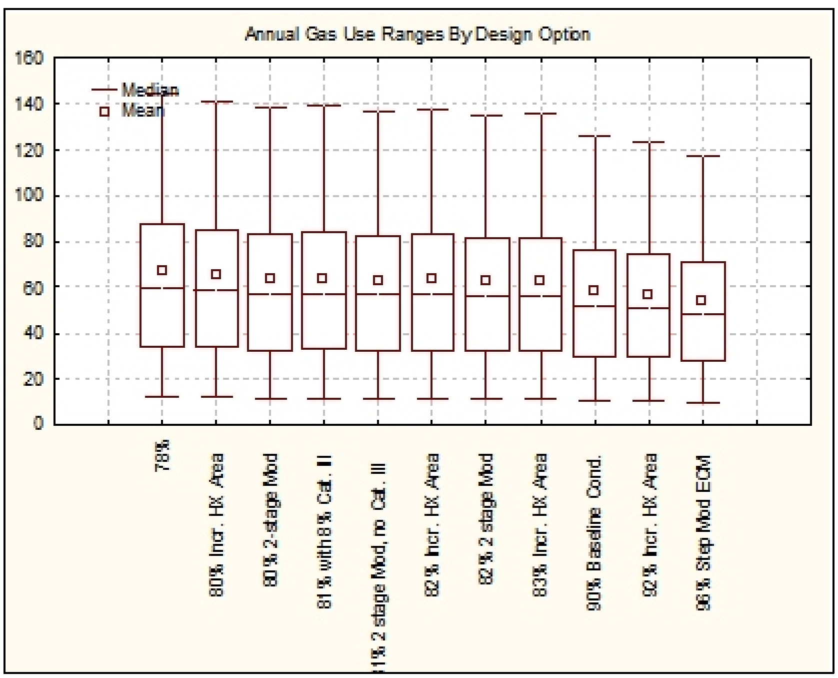

Figure 7.9.1 Range of Annual Gas Use, Non-Weatherized Gas Furnaces

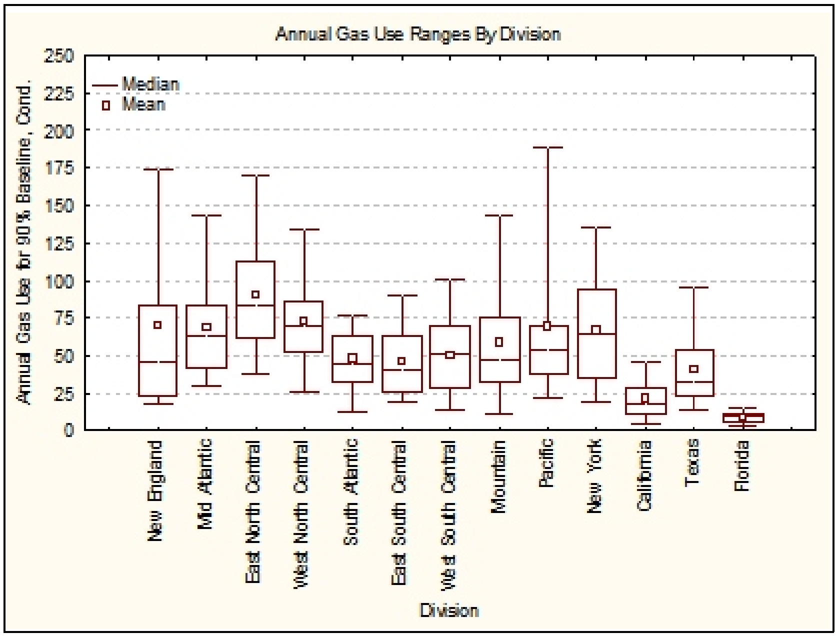

Figure 7.9.2 Range of Annual Gas Usage by Region, 90 percent AFUE, Non-Weatherized Gas Furnace

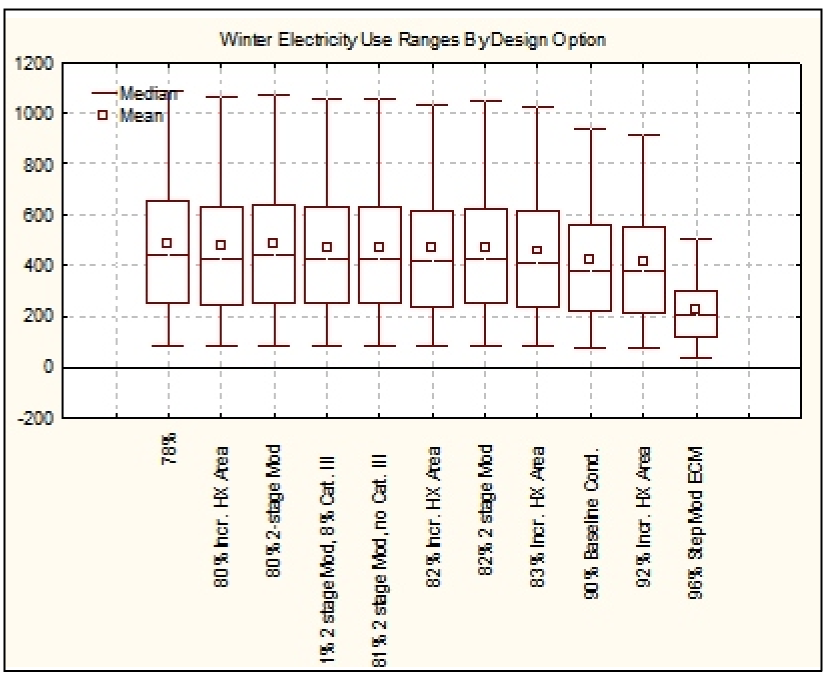

Figure 7.9.3 Range of Winter Electricity Use, Non-Weatherized Gas Furnaces

7.9.2 Weatherized Gas Furnace Energy Use

The average annual energy use for each design option for weatherized gas furnaces is shown in Table 7.9.2. The range of annual gas use for weatherized gas furnaces for each design option is shown in Figure 7.9.4. Figure 7.9.5 shows the range of winter electricity consumption.

Table 7.9.2 Weatherized Gas Furnace Energy Use

Design Option	Average Annual Gas Use (MMBtu)	Average Winter Electricity Use* (kWh)
78% AFUE - Baseline Model	40.3	298
80% AFUE - Incr. HX Area	39.3	291
80% AFUE - Improved Insulation	39.1	290
80% AFUE - Improved Heat Xfer	39.3	291
81% AFUE - Incr. HX Area	38.8	288
81% AFUE - Improved Insulation	38.7	286
81% AFUE - Improved Heat Xfer	38.8	288
82% AFUE - Incr. HX Area	38.3	284
82% AFUE - Improved Insulation	38.2	283
82% AFUE - Improved Heat Xfer	38.3	284
83% AFUE - Incr. HX Area	37.9	281
83% AFUE - Improved Insulation	37.8	280
83% AFUE - Improved Heat Xfer	37.9	281

* The average summer electricity use (for the blower) is 372 kWh for all of the design options shown.

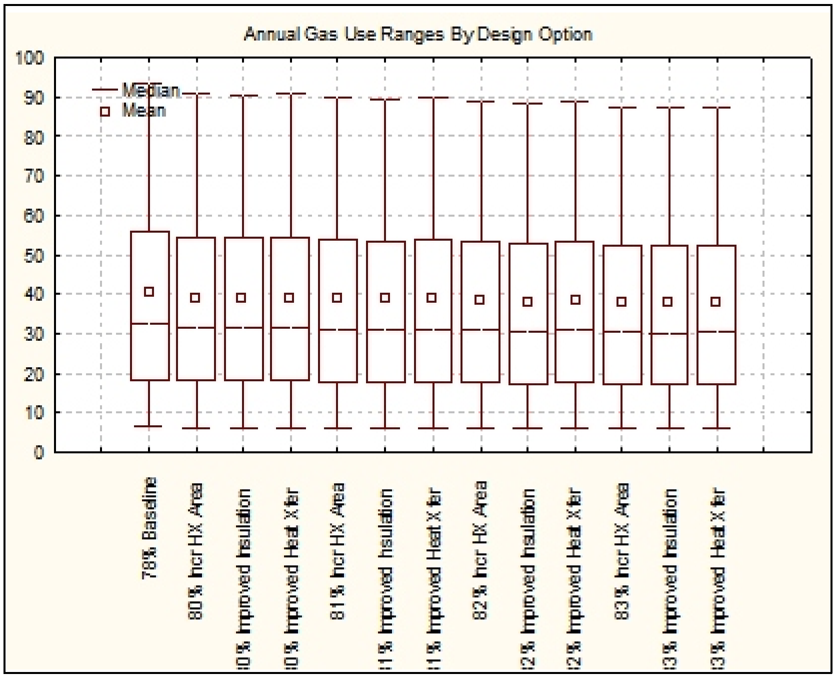

Figure 7.9.4 Annual Gas Use, Weatherized Gas Furnaces

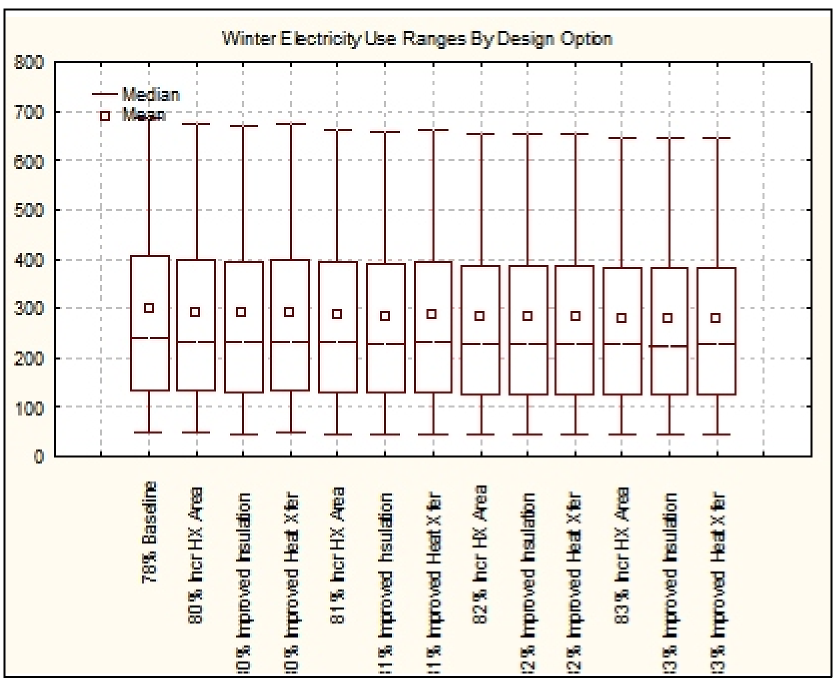

Figure 7.9.5 Winter Electricity Use, Weatherized Gas Furnaces

7.9.3 Mobile Home Furnace Energy Use

The average annual energy use for each design option for mobile home furnaces is shown in Table 7.9.3. Figure 7.9.6 shows the range of annual gas use. Figure 7.9.7 shows the range of winter electricity consumption.

Table 7.9.3 Mobile Home Furnace Energy Use

Design Option	Average Annual Gas Use (MMBtu)	Average Winter Electricity Use (kWh)*
75% AFUE - Baseline Model	51.0	374
80% AFUE - Incr. HX Area	45.2	405
80% AFUE - 2-stage Mod	44.0	415.4
81% AFUE - Incr. HX Area	44.7	400
81% AFUE - 2-stage Mod	43.5	410.6
82% AFUE - Incr. HX Area	44.1	395
90% AFUE - Condensing	40.4	360

* The average summer electricity use (for the blower) is 229 kWh for all of the design options shown.

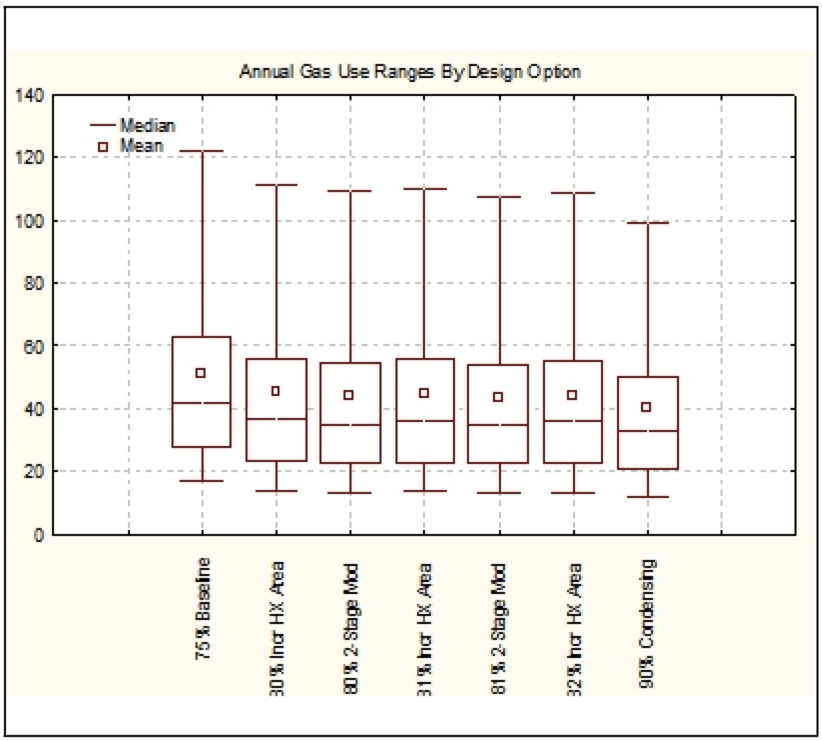

Figure 7.9.6 Annual Gas Use, Mobile Home Furnaces

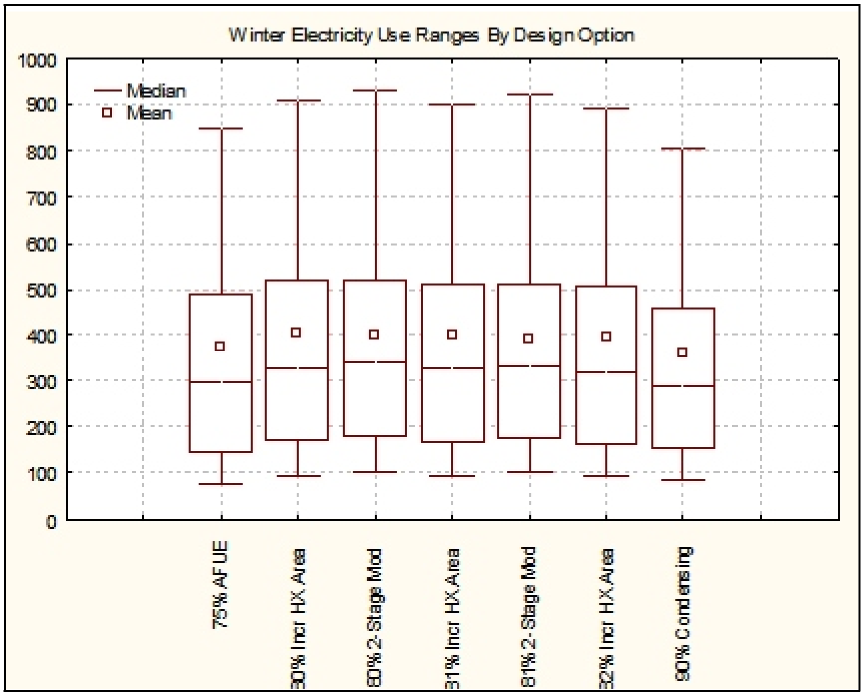

Figure 7.9.7 Winter Electricity Use, Mobile Home Furnaces

7.9.4 Oil Furnace Energy Use

The average annual energy use for each design option for oil furnaces is shown in Table 7.9.4. The range of annual gas use for each design option is shown in Figure 7.9.8. Figure 7.9.9 show the range of winter electricity consumption.

Table 7.9.4 Oil Furnace Energy Use

Design Option	Average Annual Gas Use	Average Winter Electricity Use*
78% AFUE - Baseline Model	87.8	787
80% AFUE- Incr. HX Area	85.7	768
81% AFUE- Incr. HX Area	84.7	759
81% AFUE Atom Burner 2-stage Mod.	82.6	870
82% AFUE- Incr. HX Area	83.7	750
82% AFUE Atom Burner 2-stage Mod.	81.6	860
83% AFUE- Incr. HX Area	82.7	741
83% AFUE Atom Burner 2-stage Mod.	80.7	850
84% AFUE- Incr. HX Area	81.7	733
84% AFUE Atom Burner 2-stage Mod.	79.8	840
85% AFUE- Incr. HX Area	80.8	724
85% AFUE Atom Burner 2-stage Mod.	78.9	831

* The average summer electricity use (for the blower) is 71 kWh.

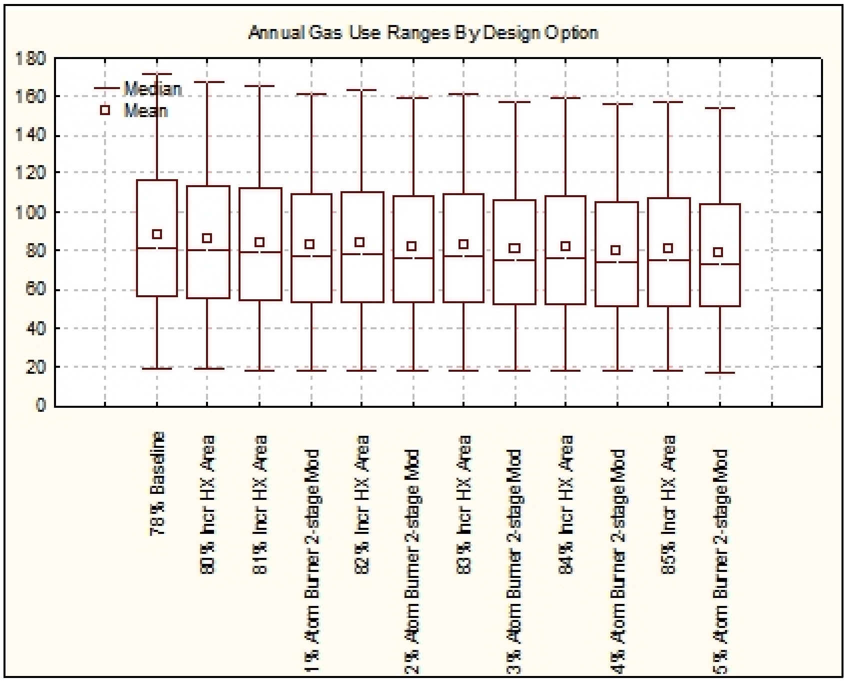

Figure 7.9.8 Range of Annual Oil Use, Oil Furnaces

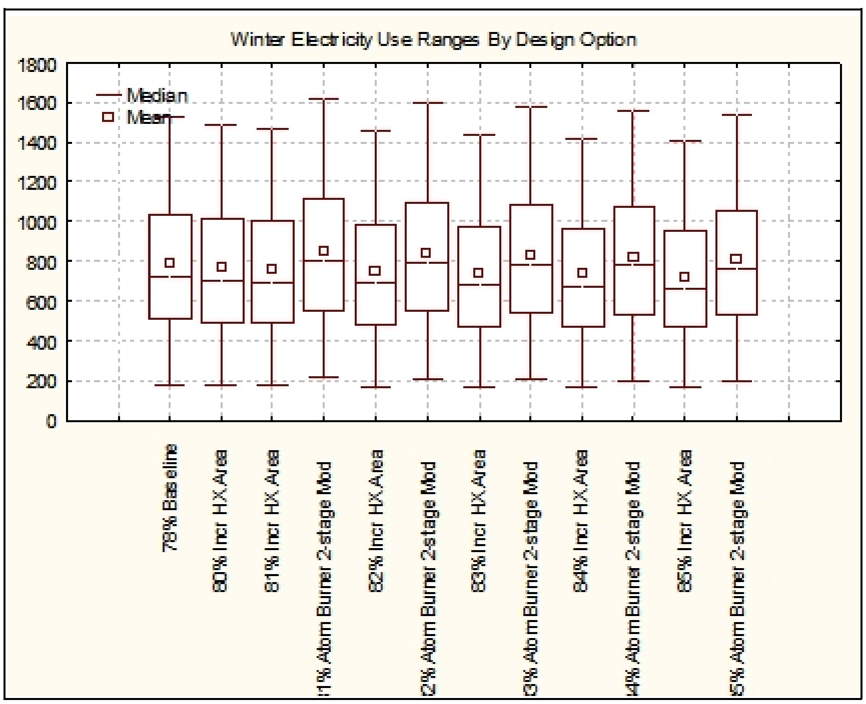

Figure 7.9.9 Range of Winter Electricity Use, Oil Furnaces

7.9.5 Gas Boiler Energy Use

The average annual energy use for each design option for hot-water gas boilers is shown in Table 7.9.5. The range of annual gas use for each design option is shown in Figure 7.9.10. Figure 7.9.11 shows the range of winter electricity consumption.

Table 7.9.5 Hot-Water Gas Boiler Energy Use

Design Option	Average Annual Gas Use (MMBtu)	Average Winter Electricity Use (kWh)
80%AFUE Baseline Model	93.5	382
81% AFUE Imp Ht Xfer / Elec. Ign	88.8	384
81% AFUE 2-stage mod. + Indc Draft	87.4	572
82% AFUE Imp Ht Xfer / Elec. Ign	87.7	379
82% AFUE 2-stage mod. + Indc Draft	86.4	565
83% AFUE Imp Ht Xfer / Elec. Ign	86.7	375
83% AFUE 2-stage mod. + Indc Draft	85.4	559
84% AFUE Imp Ht Xfer / Elec. Ign	85.7	371
84% AFUE 2-stage mod. + Indc Draft	84.4	552
88% AFUE	81.8	354
91% AFUE	79.3	304
99% AFUE	73.0	280

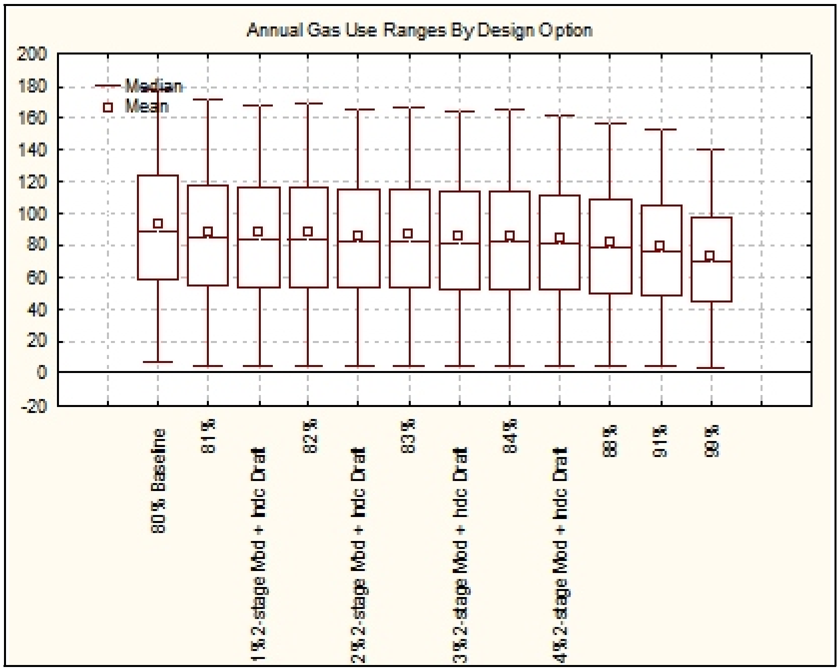

Figure 7.9.10 Range of Annual Gas Use, Hot-Water Gas Boilers

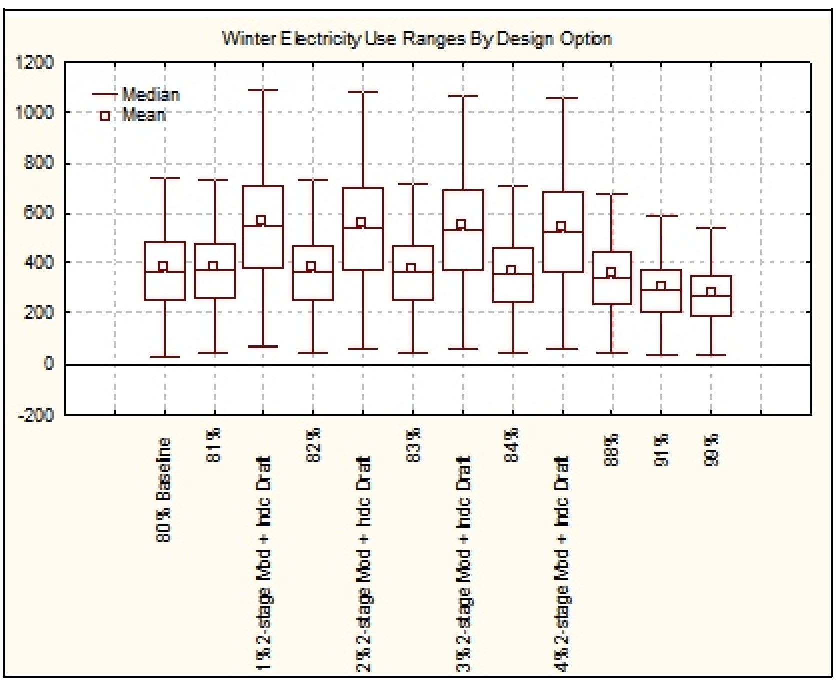

Figure 7.9.11 Range of Winter Electricity Use, Hot-Water Gas Boilers

7.9.6 Hot-Water Oil Boiler Energy Use

The average annual household energy use for each design option for hot-water oil boilers is shown in Table 7.9.6. The range of annual gas use for each design option is shown in Figure 7.9.12. Figure 7.9.13 shows the range of winter electricity consumption.

Table 7.9.6 Oil Boiler Energy Use

Design Option	Average Annual Gas Use (MMBtu)	Average Winter Electricity Use (kWh)
80%AFUE Baseline Model	108.6	418
81%AFUE	107.3	413
81%AFUE Atom Burner 2-stage Mod.	105.7	625
82%AFUE	106.0	408
82%AFUE Atom Burner 2-stage Mod.	104.4	618
83%AFUE	104.7	402
83%AFUE Atom Burner 2-stage Mod.	103.2	611
84%AFUE	103.5	398
84%AFUE Atom Burner 2-stage Mod.	102.0	604
86%AFUE	101.1	389
86%AFUE Atom Burner 2-stage Mod.	99.7	590
90%AFUE	97.0	303
95%AFUE	91.9	287

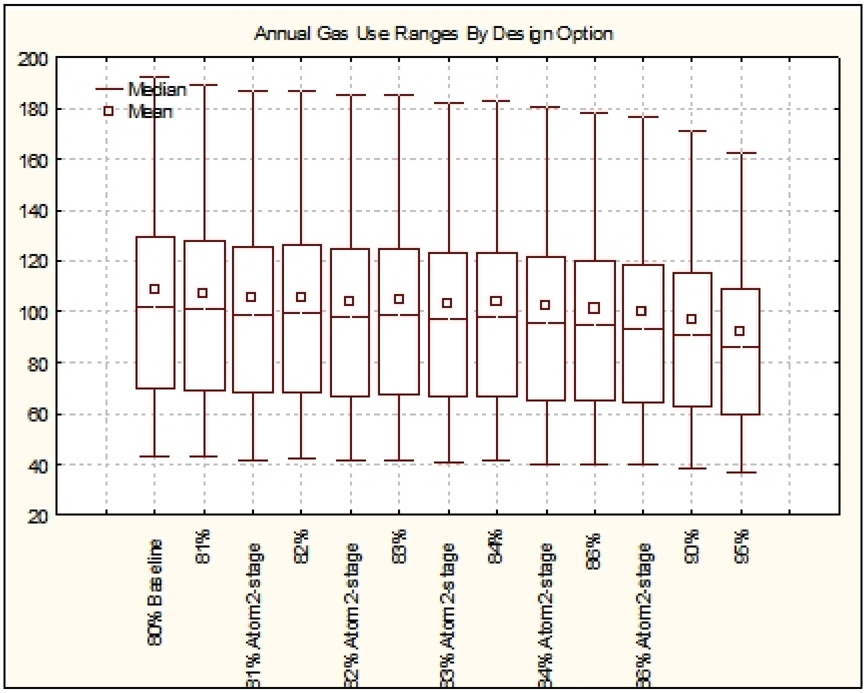

Figure 7.9.12 Range of Annual Oil Use, Hot-Water Oil Boilers

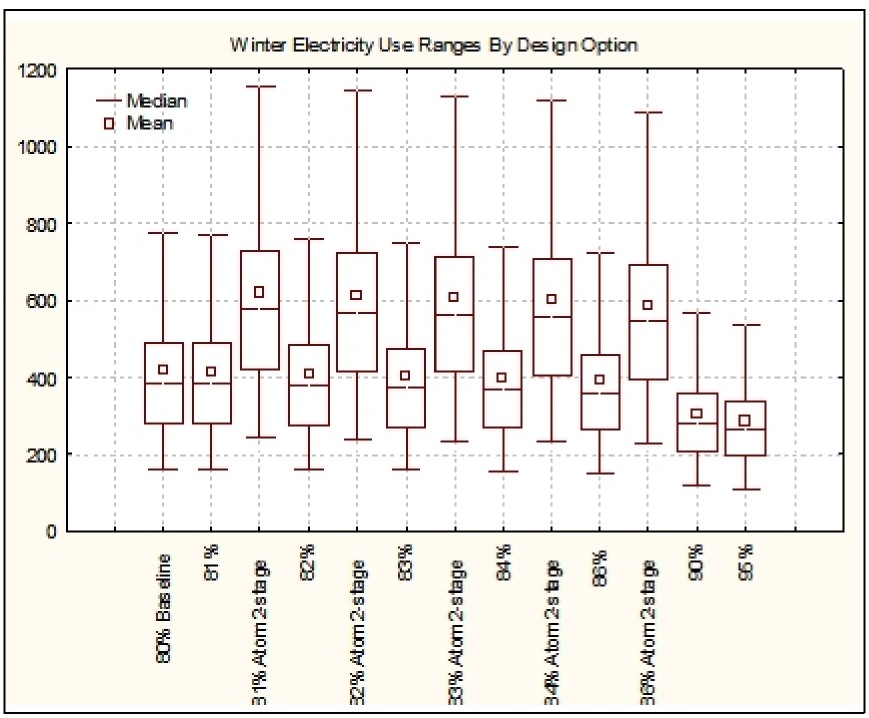

Figure 7.9.13 Range of Winter Electricity Use, Hot-Water Oil Boilers

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